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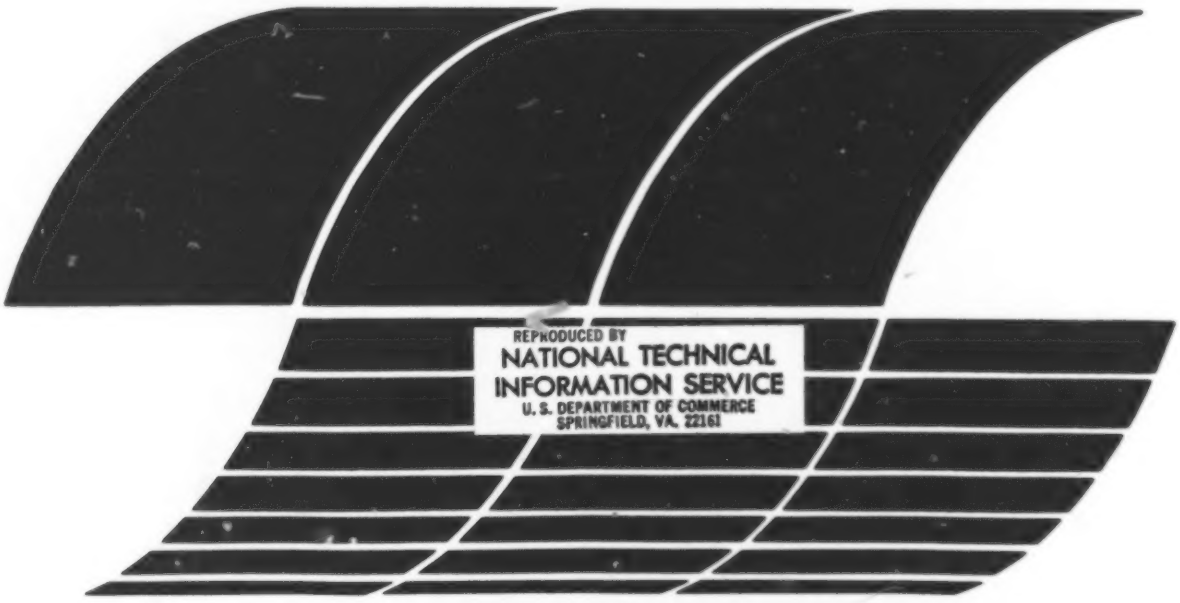
Interagency Energy/Environment R&D Program Report



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16. ABSTRACT The report gives results of a demonstration of the effectiveness of a 1700 cu m/hr (1000 acfm) University of Washington (UW) Electrostatic Spray Scrubber in controlling fine particle emissions from an electric-arc steel furnace. The two-stage portable pilot plant operates by combining oppositely charged aerosol particles and water droplets in two water spray towers. Aerosol charging sections (coronas) with negative polarity precede each spray tower. Simultaneous inlet and outlet source tests utilizing UW Cascade Impactors--Mark V for the inlet and Mark III for the outlet--provided both size-dependent and overall mass basis particle collection efficiency information. Measured overall particle collection efficiencies ranged from 58.8 to 99.5%, depending on the electrostatic scrubber operating conditions and on the inlet particle size distribution. Tabular and graphic data is presented illustrating the effects of the corona specific plate area, liquid to gas flow rate ratio, magnitudes of particle and droplet charging voltages, and electrostatic polarities on the overall particle collection efficiencies and on the particle collection efficiency as a function of particle size.

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Electrostatics	Electric Corona	Stationary Sources	20C
Scrubbers	Impactors	Electrostatic Scrubbers	07A,13I
Steel Making		University of Washington	13H
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University of Washington Electrostatic Scrubber Tests at a Steel Plant

by

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Grant No. R804393
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Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
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Washington, DC 20460

ABSTRACT

A 1,700 m^3/hr (1000 acfm) University of Washington Electrostatic Spray Scrubber was tested on an electric-arc steel furnace to demonstrate its effectiveness for controlling the emissions of fine particles. The two stage, portable pilot plant operates by combining oppositely charged aerosol particles and water droplets in two water spray towers. Aerosol charging sections (coronas) with negative polarity precede each spray tower.

Simultaneous inlet and outlet source tests utilizing University of Washington Cascade Impactors, Mark V for the inlet and Mark III for the outlet, provided both size-dependent and overall mass basis particle collection efficiency information. Measured overall particle collection efficiencies ranged from 58.8 to 99.5% depending upon the electrostatic scrubber operating conditions and upon the inlet particle size distribution. Tabular and graphical data is presented illustrating the effects of the corona specific plate area (SCA), liquid to gas flow rate ratio (L/G), magnitudes of particle and droplet charging voltages, and electrostatic polarities on the overall particle collection efficiencies and on the particle collection efficiency as a function of particle size.

Table of Contents

		Page
Abstract		iii
Table of Contents		iv
List of Figures		v
List of Tables		vii
Acknowledgements		viii
I.	Summary and Conclusions	1
II.	Recommendations	2
III.	Research Objectives	3
IV.	Description of the Source	4
V.	Experimental Equipment and Procedures	5
	A. UW Electrostatic Scrubber Apparatus	5
	B. Description of Source Test Equipment	20
VI.	Results	22
	A. Particle Collection Efficiency Tests	22
	B. Particle Collection Efficiency as a Function of Particle Size	26
	C. Particle Size Distribution Measurements	35
VII.	References	50

List of Figures

		Page
Fig. V-1.	General Layout of Electrostatic Scrubber Pilot Plant	6
Fig. V-2.	Cooling Tower Schematic	7
Fig. V-3.	Particle Charging Corona Section	9
Fig. V-4.	Collection Plate Flushing System	11
Fig. V-5.	Spray Tower #1 Nozzle Configuration	12
Fig. V-6.	Spray Tower #2 Nozzle Configuration	13
Fig. V-7.	Charged Liquor Recycle System	16
Fig. V-8.	Heated Purge Air System	19
Fig. V-9.	UW Cascade Impactor Sampling Train	21
Fig. VI-1.	Effect of Corona and Spray Voltage on Particle Collection Efficiencies	27
Fig. VI-2.	Effect of SCA and L/G on Efficiency	28
Fig. VI-3.	Effect of Charging Voltages on Particle Collection Efficiencies	29
Fig. VI-4.	Effect of Charging Polarities on Particle Collection Efficiencies	30
Fig. VI-5.	Effect of Liquid-to-Gas Flow Rate on Particle Collection Efficiencies	31
Fig. VI-6.	Effect of Liquor Charging Voltages on Particle Collection Efficiency of Spray Tower #2	32
Fig. VI-7.	Particle Collection Efficiency of Spray Towers 1 and 2 with Coronas and Mist Eliminator Off	34
Fig. VI-8.	Simultaneous Tests with Mark 5 UW Cascade Impactor at Inlet of Electrostatic Scrubber Pilot Plant	36
Fig. VI-9.	Inlet Particle Size Distributions for Tests 17, 18, 19, 20, and 21	37
Fig. VI-10.	Outlet Particle Size Distributions for Tests 17, 18, 19, 20, and 21	38
Fig. VI-11.	Inlet Particle Size Distributions for Tests 22, 23, 26, 27, 28, and 29	39
Fig. VI-12.	Outlet Particle Size Distributions for Tests 22, 23, 26, 27, 28, and 29	40
Fig. VI-13.	Inlet Particle Size Distributions for Tests 31, 32, 35, 36, 37, and 38	41
Fig. VI-14.	Outlet Particle Size Distributions for Tests 31, 32, 35, 36, 37, and 38	42

		Page
Fig. VI-15.	Inlet Particle Size Distributions for Tests 31, 32, 39, and 41	43
Fig. VI-16.	Outlet Particle Size Distributions for Tests 31, 32, 39, and 41	44
Fig. VI-17.	Inlet Particle Size Distributions for Tests 31, 32, 45, and 51	45
Fig. VI-18.	Outlet Particle Size Distributions for Tests 31, 32, 45, and 51	46
Fig. VI-19.	Inlet Particle Size Distributions for Tests 56, 57, 59, 60, 61, and 62	47
Fig. VI-20.	Outlet Particle Size Distributions for Tests 56, 57, 59, 60, 61, and 62	48
Fig. VI-21.	Inlet and Outlet Particle Size Distributions for Test 67	49

List of Tables

		Page
Table V-1.	High Voltage Power Supply Units	15
Table V-2.	Source Test Parameters and Measurement Techniques	20
Table VI-1.	Results of Tests at Electric Arc Steel Furnace	23

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Section I

SUMMARY AND CONCLUSIONS

A 1,700 m^3/hr (1000 acfm) University of Washington Electrostatic Spray Scrubber portable pilot plant was tested at an electric-arc steel furnace in Seattle to demonstrate its effectiveness for controlling the emissions of fine particles. The pilot plant consists of a cooling tower, two corona sections which charge the particles to a negative polarity, two spray towers into which positively charged water droplets are sprayed, and an electrostatic mist eliminator.

Some problems were encountered during the earlier tests resulting in lower particulate collection efficiencies than expected. The system was modified to rectify these problems and high particulate collection efficiencies were obtained throughout the particle size range. Measured overall particle collection efficiencies ranged from 58.8 to 99.5% depending upon the electrostatic scrubber operating conditions and upon the inlet particle size distribution. During the tests, the inlet particulate mass concentrations to the Electrostatic Scrubber varied from a maximum of 10.87 gm/Nm^3 (4.753 grains/SDCF) to a minimum of 0.0782 gm/Nm^3 (0.03417 grains/SDCF).

The electric-arc furnace tests showed that the particle collection efficiency increased as:

a. The aerosol and/or droplet changed from an uncharged to a charged state.

b. The gas residence time in the pilot plant increased.

c. The water to gas ratio (i.e., gal/1000 acf) increased.

d. The particles and the droplets were oppositely charged.

In conslusion, it appears that the University of Washington Electrostatic Spray Scrubber has the capability of effectively collecting fine particles at a relatively low pressure drop across the system. Further, the system has a significantly higher particle collection efficiency than a conventional water spray tower operating with no electrostatic charge.

Section II

RECOMMENDATIONS

After this year's research project on the UW Electrostatic Scrubber which consisted mainly of the extensive testing of the system at the electric-arc steel furnace, additional testing at field sites is needed in order to correlate the particle collection efficiency as a function of particle size to the design and operating parameters of this pilot plant.

We also recommend that the results from the extensive field testing program be used in comparison with theoretically predicted particle collection efficiency as a function of size.

Finally, we recommend that the pilot plant be used to demonstrate its effectiveness for simultaneous control of particulate and SO_2 emissions from coal-fired boilers.

Section III

RESEARCH OBJECTIVES

The objectives of the research performed under the auspices of Environmental Protection Agency Grant Number R803278 were to:

1. Demonstrate the effectiveness of the University of Washington electrostatic wet scrubber for controlling the emissions of fine particles from industrial sources.

2. With a portable 1,700 m^3/hr (1000 acfm) pilot plant of the University of Washington Electrostatic Wet Scrubber, obtain the data needed to design a larger electrostatic scrubber system.

Section IV

DESCRIPTION OF THE SOURCE

The UW Electrostatic Scrubber was connected to a duct exhausting from two electric-arc steel furnaces at the Bethlehem Steel Company in Seattle, Washington. This source was selected for the tests because the emission particles contain a large portion in the submicron size range. The furnaces are top charged and each furnace taps a heat of over 115 tons of refined steel every 3½ to 4 hours. Based on the mode of operation of the furnaces, the inlet particulate concentration to the Electrostatic Scrubber varied from a maximum of 10.87 gm/Nm^3 (4.753 grains/SDCF) to a minimum of 0.0782 gm/Nm^3 (0.03417 grains/SDCF).

It is reported that the fume-dust emissions during the melt period contained nonhygroscopic solid particles. The particulates consist largely of metallic oxides, such as iron oxide, zinc oxide, lead oxide, and calcium oxide. The percentages vary with each heat. A typical analysis is as follows:

- Iron oxide (Fe_2O_3) 37%
- Zinc oxide (ZnO) 35%
- Lead oxide (PbO) 7%
- Calcium oxide (CaO) 5%
- Manganese dioxide (MnO_2) 4%
- Silica (SiO_2) 3%
- Total sulfur (SO_3) 1%
- Copper oxide (CuO) 0.4%
- Miscellaneous oxides 3.5%

The furnace fumes are drawn off through an opening in the furnace roof, through a water-cooled elbow connecting the roof opening to a cylindrical vertical spray chamber where the gases are cooled down to 316°C (600°F). The flue gases are then transported through a 2.13 m (7 ft.) diameter duct for 107 m (350 ft.) to the main fan. The induced draft fan has a capacity of 220,350 Nm^3/hr (130,000 SCFM) and will develop a total head of 0.254 m (10 in.) of water. The flue gas from the main fan is exhausted to the atmosphere after passing through a baghouse.

Section V

EXPERIMENTAL EQUIPMENT AND PROCEDURES

A. UW ELECTROSTATIC SCRUBBER APPARATUS

1. Description of Overall System

The major components of the pilot plant include a gas cooling tower, an inlet and outlet test duct, two particle charging corona sections, two charged water droplet spray towers, and a mist eliminator. Auxiliary equipment includes transitional ductwork between major components and a fan. The pilot plant is housed in a 12.2 m (40 ft.) long trailer and can be easily transported to different emission sources.

The general layout of the pilot plant is shown in Fig. V-1. Incoming gases enter the top of the trailer to be treated in the vertical gas cooling tower and then turn vertically upward to enter the inlet test duct. After moving down through the inlet test duct, the gases enter the first of three horizontal passes.

The first pass contains both particle charging corona sections and the first of two water spray towers. The two coronas are at either end of this pass and are separated by spray tower #1. Spray tower #2 comprises the entire second horizontal pass and the last (third) pass contains the mist eliminator.

At the outlet of the third horizontal pass, the gases enter the top of the outlet test duct and are then directed to the fan before being exhausted through the trailer roof.

2. Cooling Tower

The cooling tower is designed to lower the gas temperature to below 121°C (250°F) in order to maintain structural integrity of the system which is constructed of steel and fiberglass reinforced plastic. The cooling tower, as shown in Fig. V-2 is 0.36 m (14 in.) in diameter x 2.98 m (9 ft. 8 in.) in height and is constructed of 12 gage T. 304 stainless steel. Cooling water is introduced through four ports spaced at 0.61 m (2 ft.) intervals on one side of the tower and is sprayed vertically upward from the tower's centerline. Four Bete Model W 10080 F full cone stainless steel nozzles used for spraying are capable of delivering up to 11.35 l/min (3.0 gpm) at 50 psig. A funnel built into the bottom of the spray tower extends through the trailer floor for cooling water removal.

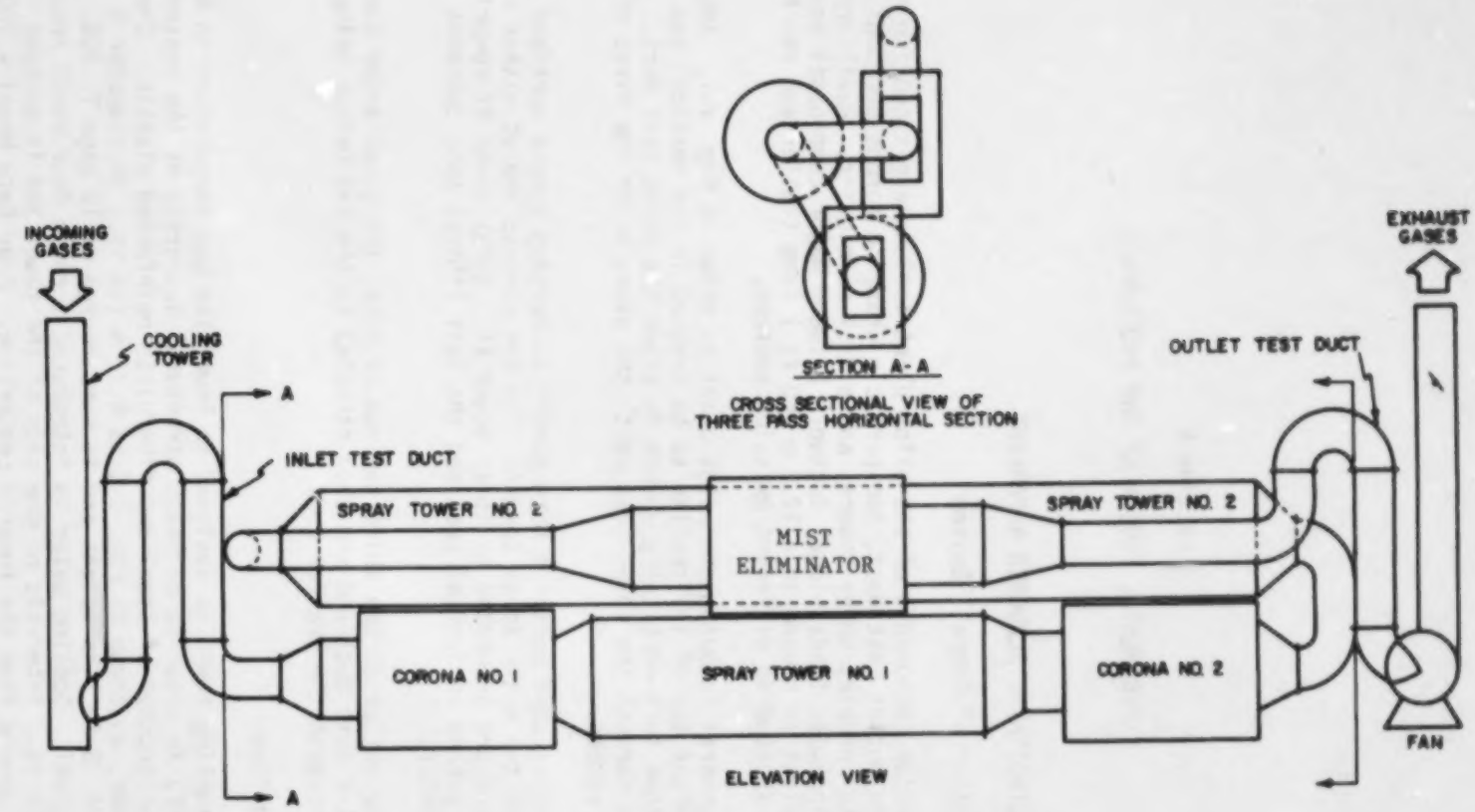

Fig. V-1. General Layout of Electrostatic Scrubber Pilot Plant

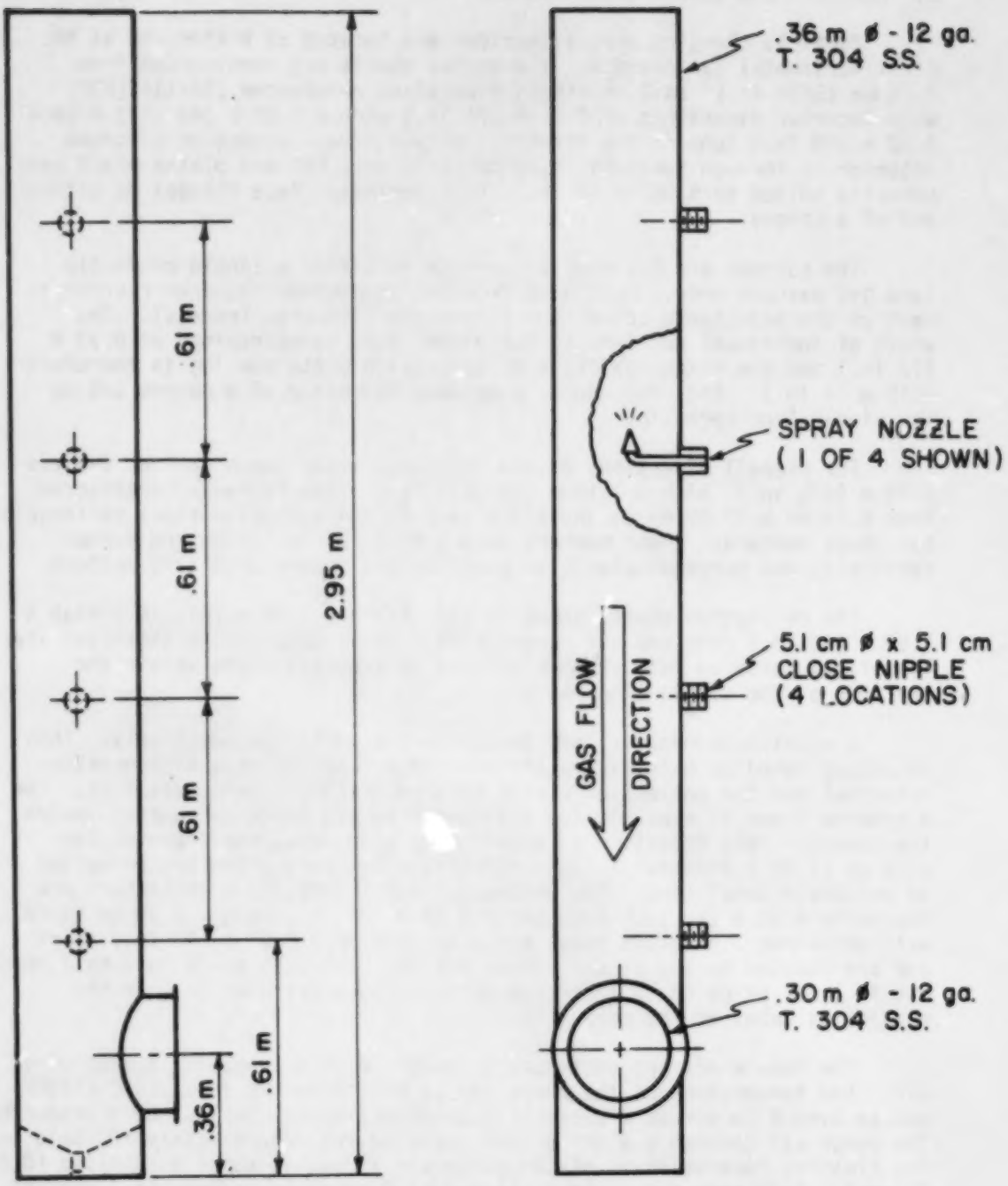

Fig. V-2. Cooling Tower Schematic

3. Particle Charging Corona Sections

Particle charging corona sections are located at either end of the first horizontal gas passage. The corona shells are constructed from 4.76 mm (3/16 in.) wall thickness fiberglass reinforced plastic (FRP) with interior dimensions of 0.61 m (24 in.) wide x 1.07 m (42 in.) high x 1.52 m (60 in.) long in the direction of gas flow. Access to a corona interior is through removable 4.76 mm (3/16 in.) FRP end plates which are normally bolted to 5.08 cm (2 in.) full perimeter face flanges on either end of a corona.

The coronas are designed to operate in either a single or double lane gas passage mode. Switching from one to another requires rearrangement of the adjustable collection plates and discharge frame(s). The width of individual gas lane(s) for either mode is maintained at 0.30 m (12 in.) and the discharge frame to collection plate spacing is therefore 0.15 m (6 in.). Fig. V-3 shows a cutaway schematic of a corona set up for single lane operation.

The overall dimensions of the discharge frame shown in Fig. V-3 are 0.70 m (27½ in.) high x 1.14 m (45 in.) long. The frame is constructed from 6.35 mm x 19.05 mm (¼ in. x 3/4 in.) T. 304 stainless steel rectangular bar stock members. Eight members each 0.69 m (27 in.) high are spaced vertically and perpendicularly to gas flow and form a grid type pattern.

The collection plates shown in Fig. V-3 are 1.05 m (41¼ in.) high x 1.50 m (59 in.) long and are constructed from 11 gage T. 316 stainless steel. The plates serve as full chamber baffles to keep the gases within the confines of the single lane passage.

A negative corona is used to charge the particles negatively. This is accomplished by maintaining the discharge frame(s) at a high negative potential and the collection plates at a neutral or ground potential. The discharge frame is electrically isolated from all other components inside the corona. This isolation is provided by suspending the frame on two 2.54 cm (1 in.) diameter T. 303 stainless steel rods which are connected to porcelain insulators. The Ceramaseal Model 902B1353-6 insulators are housed in 0.30 m (12 in.) diameter x 0.61 m (24 in.) long x 6.35 mm (¼ in.) wall thickness plexiglass tubes which are centered 1.07 m (42 in.) apart and are located on top of the corona shells. Two 0.30 m (12 in.) to 0.36 m (14 in.) x 7.62 cm (3 in.) FRP reducting flanges are used to join the plexiglass tubes to the corona top.

The insulators are continually flushed with a supply of heated purge air. The temperature of the purge air is maintained at about 49°C (120°F) and an even flow across a plexiglass tube section is obtained by introducing the purge air through a distribution plate having approximately 10% hole area. The flushing face velocity of the purge air is set at about 0.18 m/sec (0.6 ft/sec). This same purge air distribution flange also serves as a support flange in that an insulator, and hence the discharge frame(s), is bolted directly to it. The high voltage lead-in to the discharge frame is through one of the two feed-through type insulators.

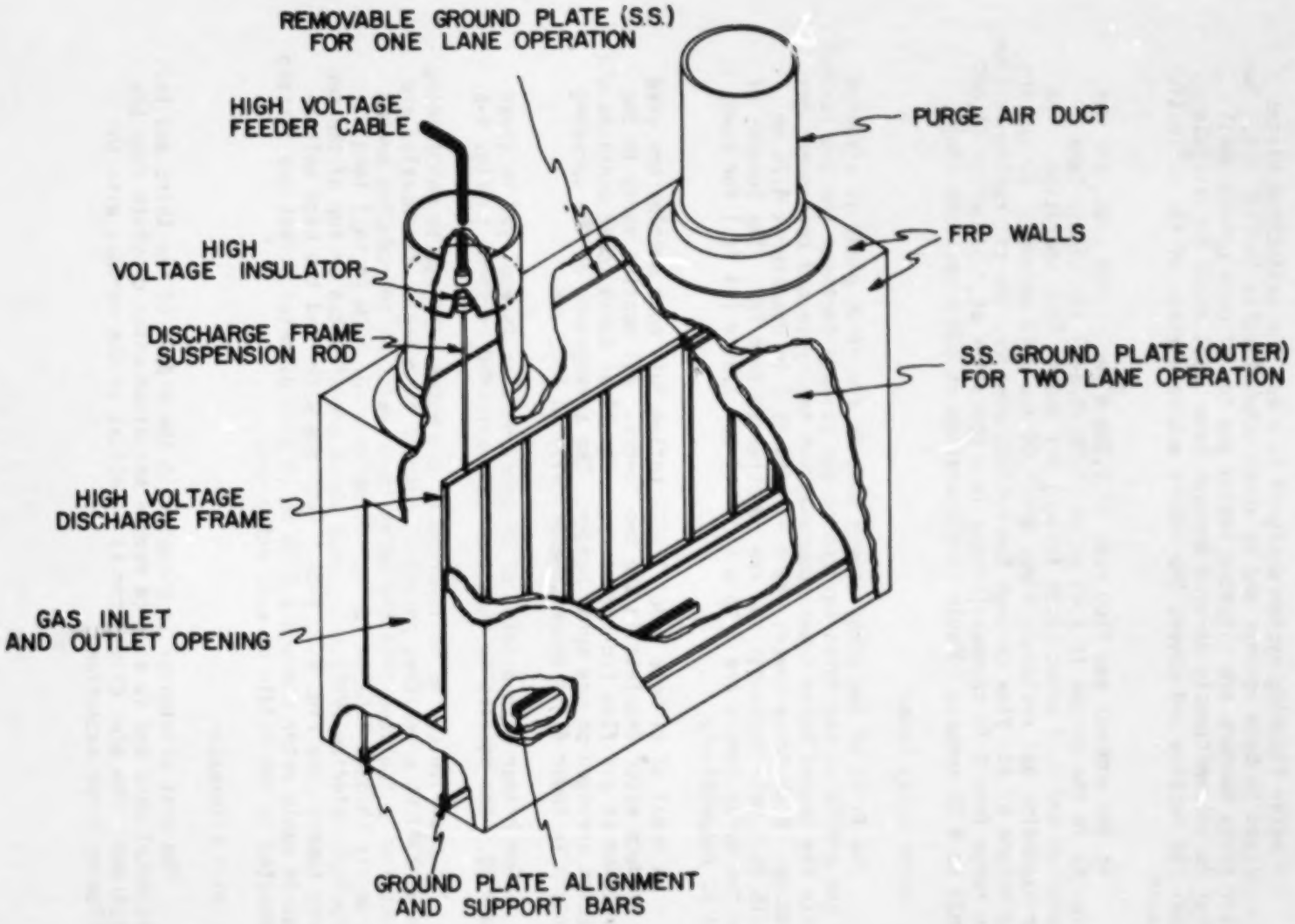

Fig. V-3. Particle Charging Corona Section

A water flushing system designed to clean the collection plates is utilized in both coronas and is shown schematically in Fig. V-4. Two water spray headers are situated inside the top of each corona shell. Water is intermittently sprayed through Bete Model 45080 80° stainless steel fan nozzles and covers the entire active portion of the collection plates.

At the nominal gas flow rate of 1,700 m^3/hr (1,000 cfm), the gas velocity in the corona is 1.45 m/sec (4.76 ft/sec) for single lane operation and 0.72 m/sec (2.38 ft/sec) for double lane operation. The corresponding gas residence times are 1.05 and 2.10 seconds. By varying the volume of air flow through the system, however, the gas residence time can range from 0.70 seconds (single lane operation at 2,548 m^3/hr (1,500 cfm)) to 4.20 seconds (double lane operation at 850 m^3/hr (500 cfm)).

4. Water Spray Tower

The first of two spray towers used in the pilot plant is situated in the middle of the first horizontal gas passage (between the two coronas) while the second spray tower comprises the entire second horizontal gas passage. Both spray towers are 0.91 m (3 ft.) in diameter x 4.76 mm (3/16 in.) wall thickness and are constructed from FRP. The lengths of the two spray towers are 3.05 m (10 ft.) and 7.36 m (24 ft.) for tower #1 and #2 respectively.

A total of 21 Bete Model TFGFCN teflon full cone nozzles are used to produce water droplets in the two towers. All nozzles spray in the direction of gas flow (co-currently). The first spray tower contains six nozzles arranged on one spray header. The arrangement of the spraying pattern in tower #1 is shown schematically in Fig. V-5.

One header with a total of 16 spray nozzles is employed in spray tower #2. The nozzles in this tower are arranged as shown in Fig. V-6.

A positive charge is imparted to the water droplets by maintaining the nozzles at a positive potential (direct charging). The nozzles are electrically isolated from the spray tower walls by introducing heated purge air through 7.62 cm (3 in.) diameter x 10.16 cm (4 in.) long polyvinyl chloride (PVC) entry caps which are situated on top of the two spray towers (see Fig. V-5, V-6). Both the water and the high voltage lead-in cable enter through a 6.35 mm (¼ in.) diameter street tee fitting connected to the middle of each entry cap.

5. Mist Eliminator

The mist eliminator is situated in the middle of the third and last horizontal pass and is used to remove entrained water droplets from the airstream. The mist eliminator is identical to the coronas with the following three exceptions:

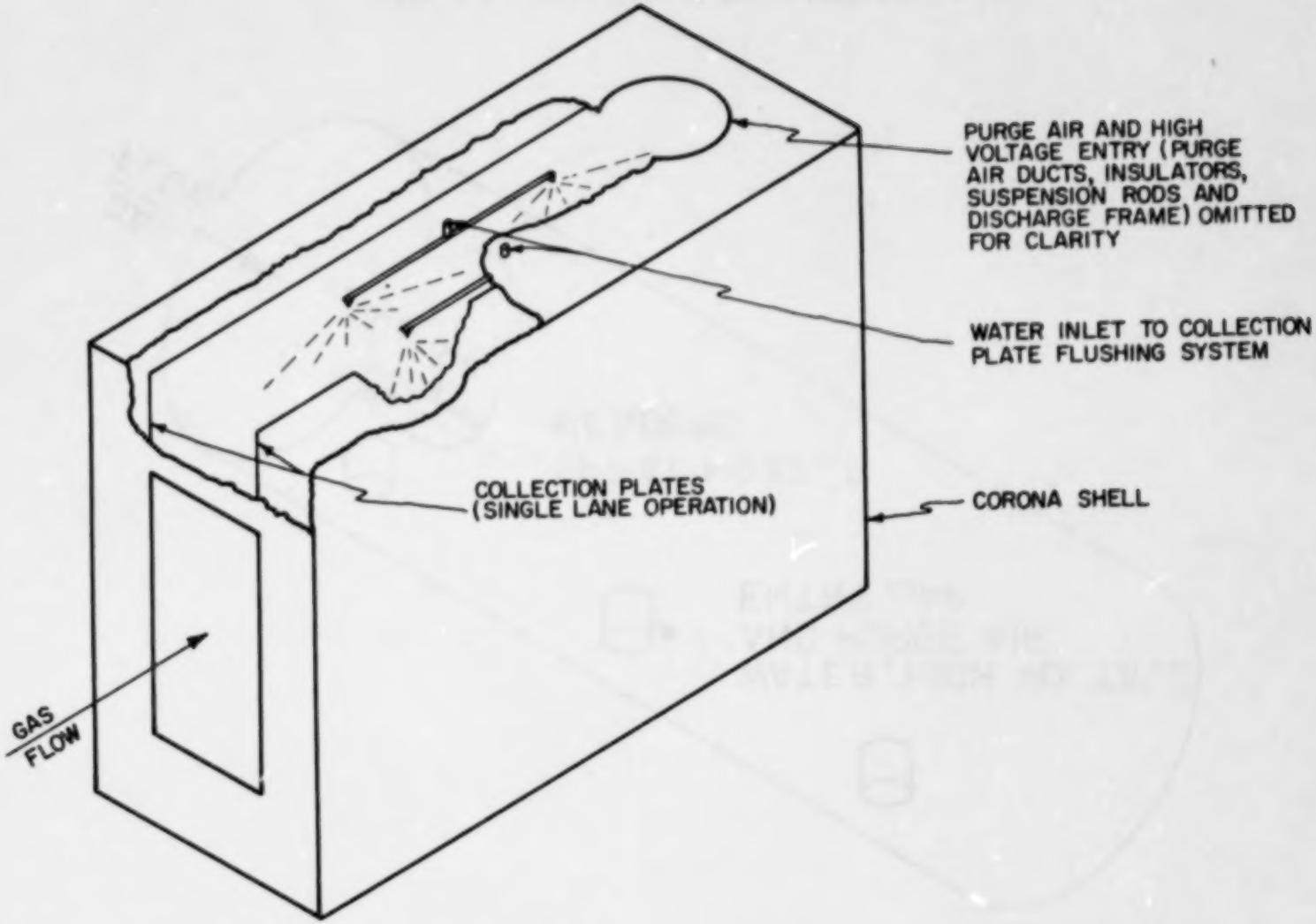
PURGE AIR AND HIGH VOLTAGE ENTRY (PURGE AIR DUCTS, INSULATORS, SUSPENSION RODS AND DISCHARGE FRAME) OMITTED FOR CLARITY
WATER INLET TO COLLECTION PLATE FLUSHING SYSTEM
COLLECTION PLATES (SINGLE LANE OPERATION)
CORONA SHELL
GAS FLOW

Fig. V-4. Collection Plate Flushing System

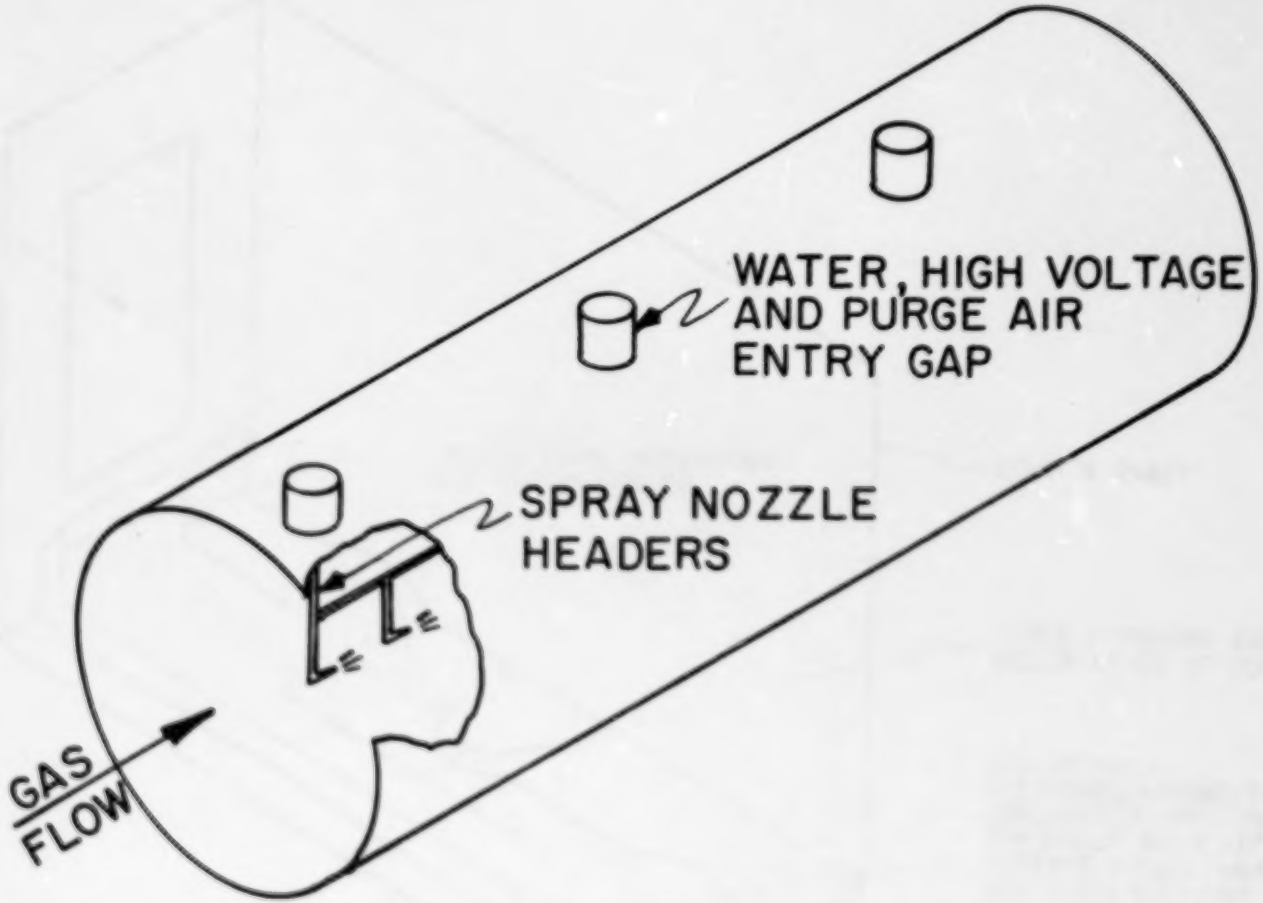

Fig. V-5. Spray Tower #1 Nozzle Configuration

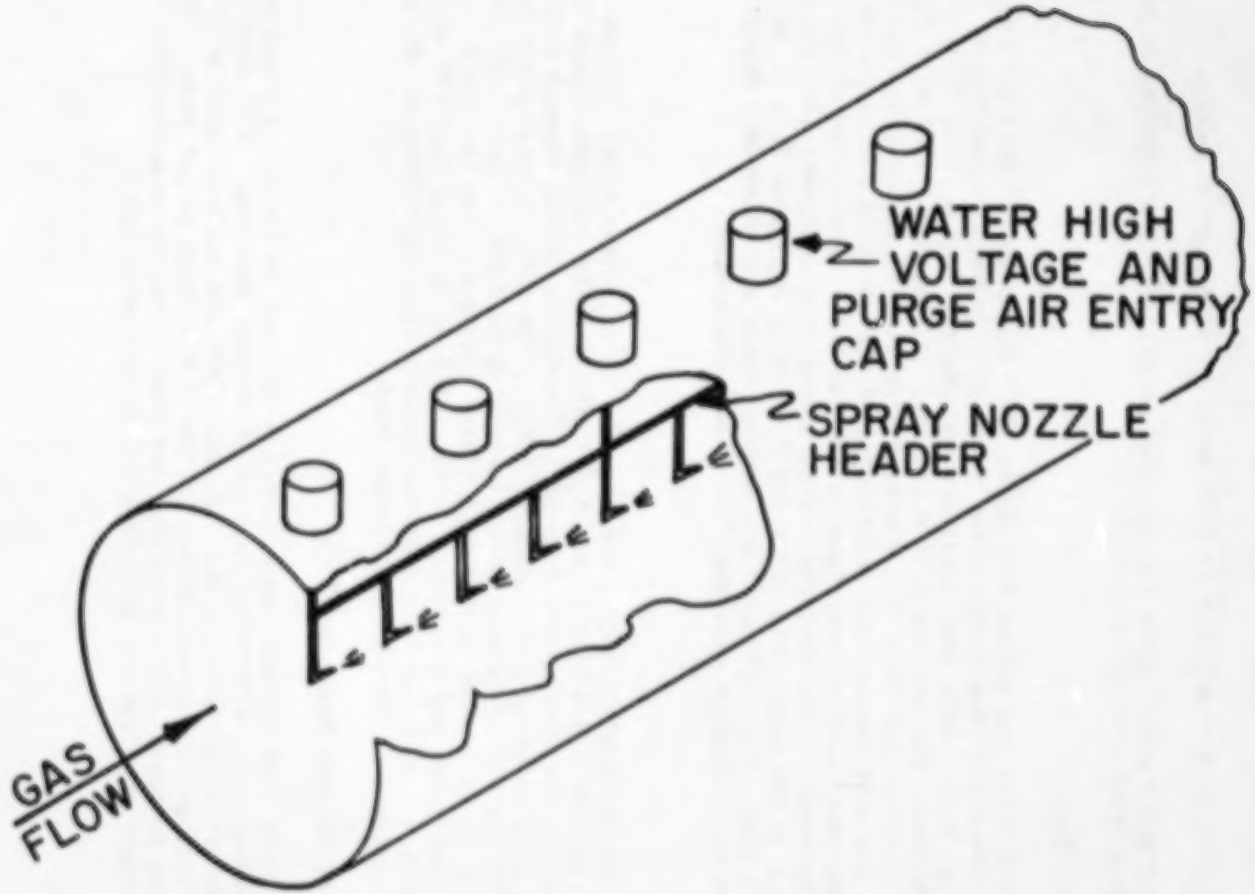

Fig. V-6. Spray Tower #2 Nozzle Configuration

1. The discharge frame is maintained at a positive potential.

2. The mist eliminator is not equipped with a collection plate flushing system.

3. The mist eliminator is 5.08 cm (2 in.) shorter in height.

The last point noted above necessitates an equivalent shortening of the discharge frame and collection plates.

6. Test Ducts

The inlet and outlet test ducts are located immediately before the first corona and immediately after the mist eliminator respectively (see Fig. V-1). Both test ducts are constructed from 4.76 mm (3/16 in.) wall thickness FRP and are 0.30 m (12 in.) in diameter x 1.22 m (4 ft.) long. Vertical gas flow in a downward direction is employed because it allows the most conventient positioning of the particle sizing source test equipment used as described in Section V-B, "Description of Source Test Equipment." The particle sizing source test equipment also dictated the size of the test ports which are 7.62 cm (3 in.) wide x 15.24 cm (6 in.) high. The test ports are located three duct diameters downstream and one duct diameter upstream from flow disturbances.

7. Fan

The fan used to induce the air flow (i.e., clean side) through the pilot plant is a New York Blower Model RFE-12. The straight-bladed fanwheel and housing are constructed from FRP. The fan is driven through a split pulley belt drive by a Westinghouse 5 h.p., 208 volt, 3-phase motor turning at 1,800 rpm and is capable of delivering up to 2,548 m^3/hr (1,500 cfm) at 20.32 cm (8 in.) water column (WC) static pressure. The fan has a horizontal inlet and a vertical outlet. A 4.76 mm (3/16 in.) FRP wall thickness x 0.30 m (12 in.) diameter exhaust duct containing an adjustable damper extends up through the trailer roof.

8. High Voltage Power Supplies

Three high voltage power supply units used in the pilot plant serve the coronas, mist eliminator, and water droplet charging. All three units operate off a 110 volt, 60 Hz, 1 ϕ supply and are equipped with multi-range voltage and current meters on the high voltage output side. The units are also equipped with overvoltage and overcurrent surge protection. The three power supplies are described in the following table.

Table V-1. High Voltage Power Supply Units

Source	Model	Polarity	Rated Output	
			kV	mA
Coronas	Universal Voltronics	Negative	70	25
Mist Eliminator	Hipotronics #860-16	Positive	60	16
Droplet Charging	Hipotronics #825-40	Positive	25	40

9. Water Supply System

a. General

The water supply system for the scrubber is controlled from a single control panel situated on an interior side wall proximate to the inlet test duct. Two different sources supply water to this control panel: recycled water and fresh water. The positively charged recycle water is used as scrubbing liquor in spray towers #1 and #2 and the fresh water (uncharged) is used in the flushing systems and the cooling tower.

b. Water recycle system

A water recycle system was designed to satisfy the following requirements:

1. Water flow rate of 30 gal/min
2. Water pressure of 40 psi (at nozzles)
3. Closed system with make-up capability
4. Continuous removal of particles greater than 30 microns.

The entire water plumbing system was redesigned to accommodate the 30 gal/min maximum flow rates as well as minimize frictional losses for more economic pumping. PVC piping and nonconductive high pressure hose were used. A schematic of the water recycle system is shown in Fig. V-7.

A larger teflon spiral nozzle (Bete TF6TCN) was chosen since it resists plugging by particles in the recycled water and is capable of creating a relatively small droplet at higher flow rates. The total number of nozzles was reduced to 21. Spray tower #1 has six nozzles and is designed for a flow rate of 10 gal/min while spray tower #2 has 15 nozzles and is designed for 20 gal/min.

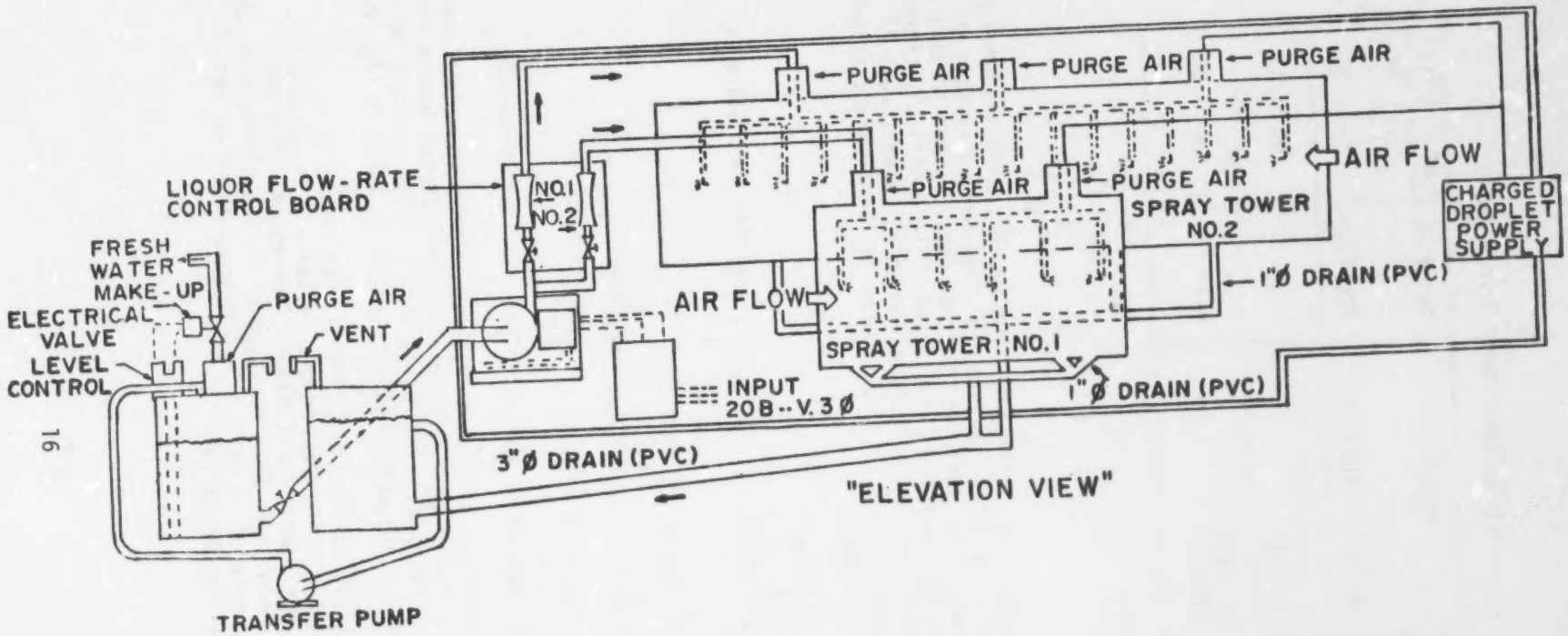

Fig. V-7. Charged Liquor Recycle System

A Goulds centrifugal pump model 3196ST was chosen to satisfy the water flow rate and pressure head requirements. Since the spray charging is achieved by applying from 0 to 30 kV at the throat of each nozzle, the pump will also be at an elevated potential. It is therefore electrically isolated on a micarda base with a FRP cover.

The sprayed water is drained from the spray towers into a 135 gallon settling tank. The settling tank acts as an elutriation chamber designed such that particles greater than 30 microns in diameter will settle out with a maximum water flow rate of 30 gal/min. A 3 hp, 3,600 rpm, 110 V, 1 Ø Deming centrifugal pump transfers the recycled water from the settling tank through sprays into the sump tank at a maximum rate of 30 gal/min. From the sump tank the water is recycled back into the spray towers by the Goulds pump previously described.

The sump tank is equipped with a liquid level control and fresh water make-up capability. The Sethco Liquid Level Control is a three function controller which operates on the action of captive air pressure in a CPVC column. When the water level in the sump tank is sufficiently high, no make-up water is injected. When the sump tank water level drops to a pre-set middle level, the level controller will signal an electrically actuated ball valve to open and allow fresh make-up water to flow into the tank. When the water level in the tank becomes dangerously low, the level controller will activate a relay switch which will shut the pump off. When a pre-determined amount of fresh make-up water is desired for dilution purposes, a spray from the water control board can be regulated to allow continuous make-up water addition.

10. Fresh Water System

The three applications for fresh (uncharged) water are described below:

1. Test duct cleaning system

   One Bete Model W10080F full cone stainless steel spray nozzle is positioned at the top of both the inlet and outlet test ducts. Since only infrequent cleaning is required at these locations, water flow is not monitored.

2. Corona collection plate flushing system

   The details of these two users have been specified in Section V-3, "Particle Charging Corona Sections." The flow rate is not monitored.

3. Cooling tower spray system

   This user, described in Section V-2, "Cooling Tower," is equipped with a Fisher-Porter Model 2235631 3.8-41.6 l/min (1-11 gpm) Ratosight rotometer.

11. Purge Air Heating System

The new purge air heating system is schematically illustrated in Fig. V-8. The system consists of both commercially available and custom built components. The fan is a Barry Blower model BUF-90 Junior Fan employing a 1/3 HP motor with a maximum capacity of 500 cubic feet per minute. The discharge air then passes through a custom designed Nelco Duct Heater. It is a 19kw heating unit with 4 stages to regulate the degree of heating required. The duct heater operates on 308V, 3ϕ power with a 110V control source which is external of the heater. A custom designed distribution plenum follows the heater and provides an adjustable purge air supply to the high voltage access points on the two corona sections, the mist eliminator section and the current limiting device for the liquid make up to the sump tank. The basic design criterion for the purge air system is to provide 150^{0}F purge air at a rate of up to 500 cfm (total).

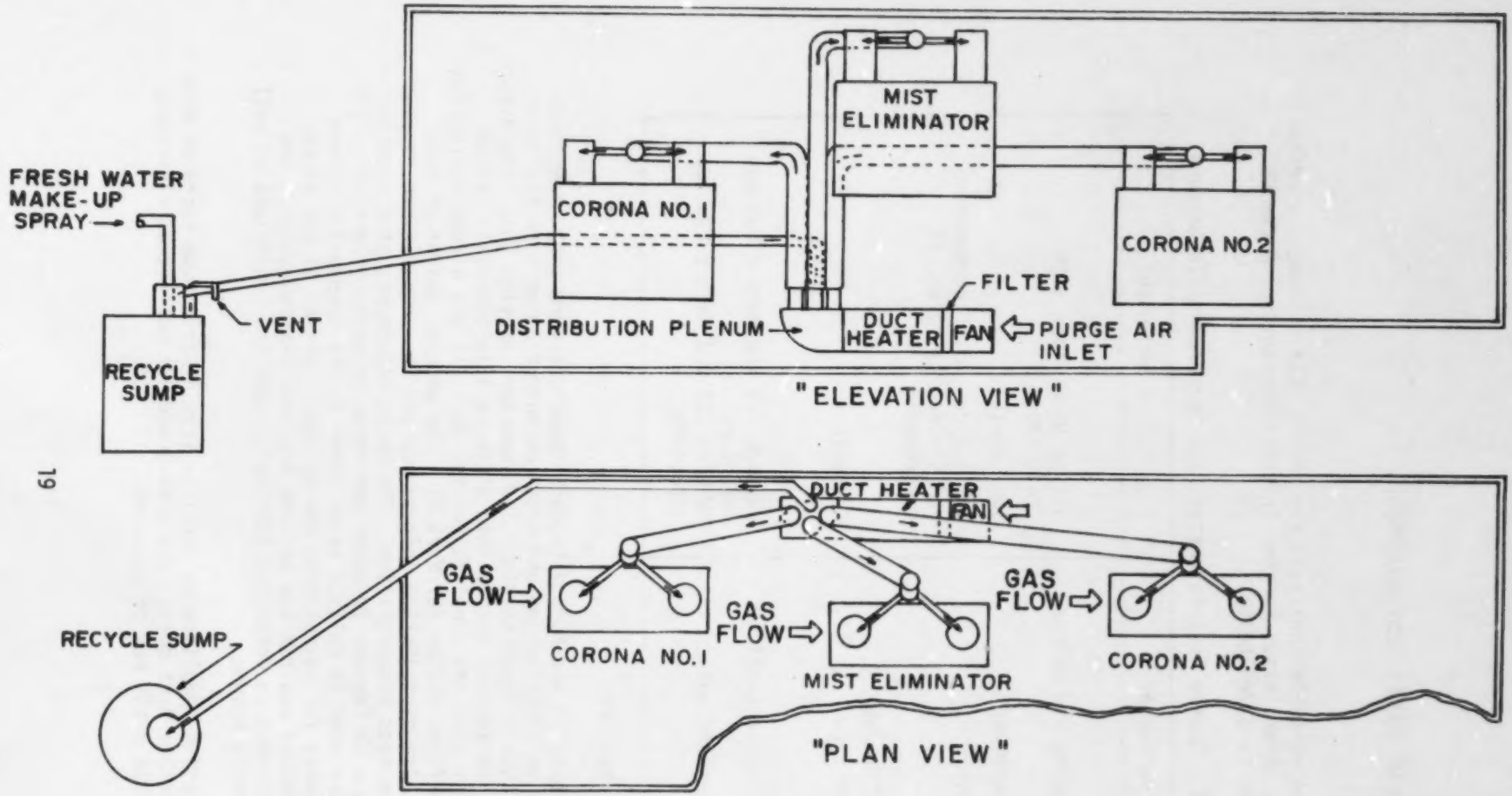

Fig. V-8. Heated Purge Air System

B. DESCRIPTION OF SOURCE TEST EQUIPMENT

1. General

The following table indicates the source test equipment used to measure various parameters. Further information concerning the UW Cascade Impactor is given below.

Table V-2. Source Test Parameters and Measurement Techniques

Parameter	Equipment
1. Air	
a. Velocity and volume	S-type pilot tube with draft gauge
b. Temperature	Thermometer
c. Moisture	Wet and dry bulb thermometer and checked by volume of condensate
2. Water Spray Towers	
a. Water flow	Rotometers
3. Aerosol	
a. Mass concentration	UW Mark III and Mark V Cascade Impactors
b. Size distribution	UW Mark III and Mark V Cascade Impactors

2. UW Cascade Impactor

The UW Mark III and Mark V Cascade Impactors were used to measure both particle size distribution and mass concentration at both the inlet and outlet test ducts respectively. The impactors provide this information by segregating the aerosol sample into discrete size intervals (seven collection plates plus one final filter for Mark III and eleven collection plates plus one final filter for Mark V). The aerosol weight on each plate provides size distribution information and the total weight is used to determine the mass concentration. The basic components of a sampling train utilizing a UW Cascade Impactor are shown schematically in Fig. V-9. The impingers are used to collect water vapor in the sample air stream and provide a basis for calculating the moisture content of gas stream which may be checked against the wet and dry bulb determination. The dry gas meter is used to determine isokinetic sampling conditions as well as the total sample volume.

By conducting simultaneous particle size distribution tests at both the inlet and outlet test ducts, the size-dependent collection efficiency curve of the pilot plant may be measured.

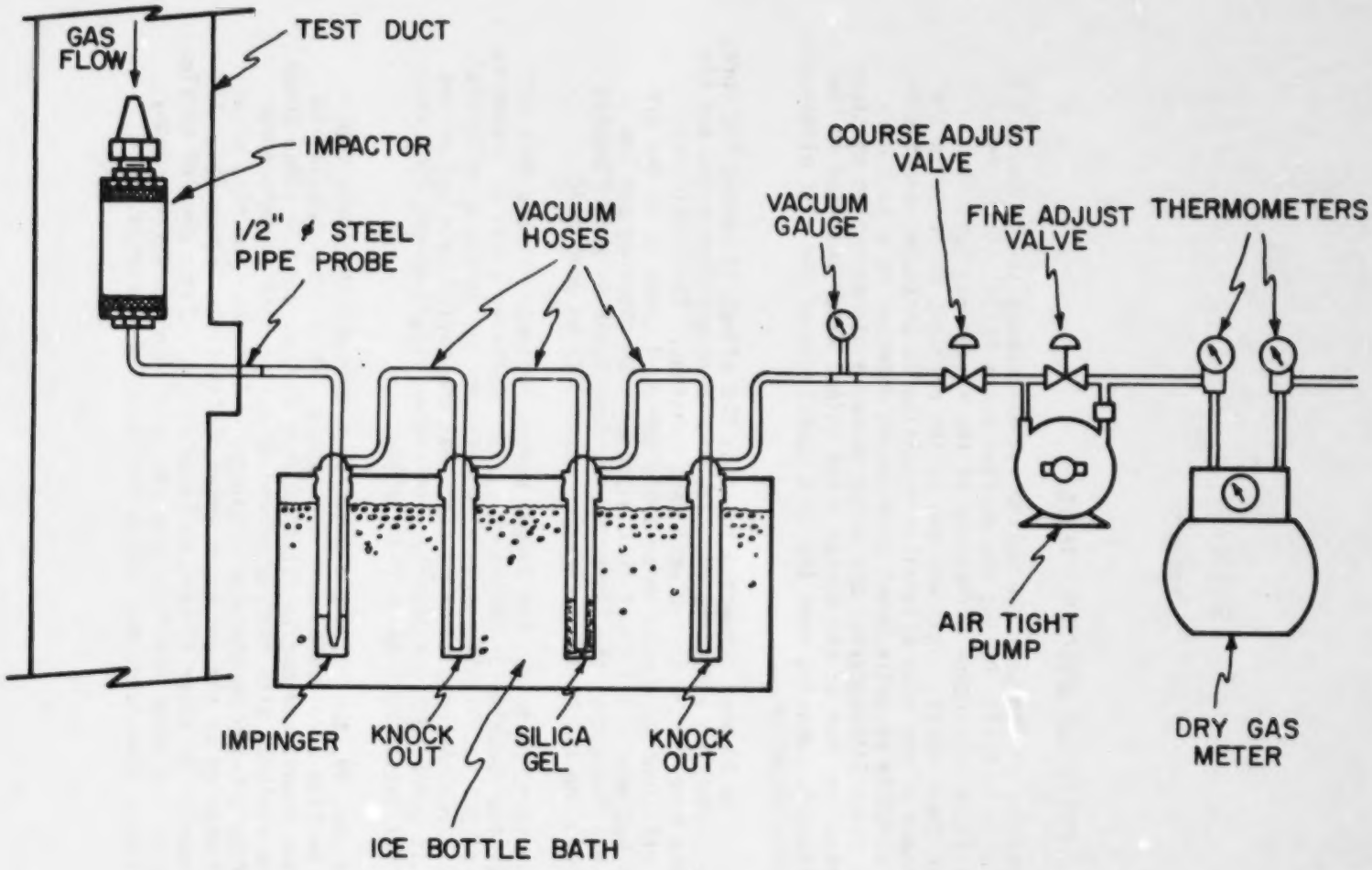

Fig. V-9 UW Cascade Impactor Sampling Train

Section VI

RESULTS

A. PARTICLE COLLECTION EFFICIENCY TESTS

The results of the particle collection efficiency source tests are presented in Table VI-1. During the earlier tests (1-16) it was found that the particle collection efficiency of the system was less than expected for these tests. This was due to the particle build-up in the duct downstream of the mist eliminator resulting in particle re-entrainment. The particle re-entrainment problem was detected by a test performed with clean (atmospheric) air which showed a higher outlet particulate concentration than at the system inlet (clean water was used as the scrubbing liquor). Washing down the duct downstream of the mist eliminator corrected this situation.

Tests 17 to 21 were conducted to study the effect of corona and spray voltages on collection efficiencies. The liquid-to-gas flow ratio and the gas residence time in the system were kept constant. The particulate collection efficiencies during these tests improved compared to the previous tests but were still lower than expected. On checking out the system, it was found that the liquor sprays from tower #1 were flooding corona #2 reducing the particle charging capability of corona #2.

During tests 22 to 29, the liquor sprays to tower #1 were shut off to eliminate the flooding of corona #2. These tests were run to determine the effect of SCA and liquid-to-gas flow ratio on the particle collection efficiency. From the results it is seen that the particulate collection efficiency is enhanced significantly with higher liquid-to-gas flow ratio and higher gas residence time in the system.

After test 29, the pilot plant was shut down and the spray towers and corona section were washed down thoroughly. Of the six nozzles in tower #1, the downstream nozzle fittings were plugged and the other three nozzles were replaced with nozzles providing a fine mist (manufacturer data specifies 200-300 μm diameter droplets). A screen-type mist eliminator was installed at the outlet of tower #1 (inlet to corona #2). All the spray nozzles in tower #2 were replaced with the finer droplet nozzles. The purpose of the above modifications was to obtain smaller droplets, lower the liquor flow rate, and reduce the flooding of corona #2.

Table VI-1 Results of Tests at Electric Arc Steel Furnace

Test No.	Gas Flow at Outlet Duct (acfm)	Water to Average Gas-flow Ratio (gal/1000 acf)	Voltage (kV)		Collection Efficiency (%)	Outlet Conc. (gr/scf)
			Corona	Spray		
			#1 #2	#1 #2		
1	1,783	13.6	-70 -70	+15 +15	94.2	0.0057
2	1,484	17.8	-35 -35	+15 +15	94.0	0.0025
3	1,553	17.8	-70 -70	+20 +20	98.1	0.0024
4	1,032	23.4	-70 -70	0 0	95.3	0.0016
5	1,474	17.6	-70 -70	+15 +15	92.6	0.0395
6	1,428	23.7	-70 -70	+10 +10	97.4	0.0025
7	1,391	24.2	-70 -70	+20 +20	87.9	0.0075
8	1,281	24.3	-50 -50	0 0	89.0	0.0978
9	1,470	23.2	-50 -50	+20 +20	80.2	0.0750
10	1,214	26.8	-50 -50	+10 +10	81.0	0.0811
11	1,331	25.7	-70 -70	+20 +20	91.0	0.0430
12	1,281	24.3	-70 -70	0 0	85.6	0.0178
13	1,210	25.2	0 0	+20 +20	83.7	0.1042
14	1,225	24.5	0 0	0 0	80.4	0.16797
15	1,259	23.1	0 0	+10 +10	58.8	0.33031
16	1,225	0	-70 -70	0 0	87.9	0.07380
17	1,189	26.5	-70 -70	+20 +20	93.4	0.0442
18	1,174	26.2	-68 -68	+10 +10	96.6	0.0285
19	1,163	25.5	-68 -68	0 0	97.9	0.0269
20	1,175	26.5	-70 -70	+10 +10	97.3	0.0313
21	1,148	26.1	0 0	+10 +10	88.8	0.1151
22	1,221	21.1	-70 -70	0 +10	97.7	0.0194
23	1,247	20.4	-70 -70	0 +10	96.4	0.0258
24	1,293	20.8	-65 -65	0 0	93.3	0.0315
25	1,184	22.4	-70 -70	0 0	98.2	0.0074

Table VI-1 Results of Tests at Electric Arc Steel Furnace (cont.)

Test No.	Gas flow at Outlet Duct (acfm)	Water to Average Gas-flow Ratio (gal/1000 acf)	Voltage (kV)				Collection Efficiency (%)	Outlet Conc. (gr/scf)
			Corona		Spray			
			#1	#2	#1	#2		
26	905	32.3	-65	-65	0	+10	99.1	0.00344
27	953	31.8	-65	-65	0	+10	98.9	0.00524
28	1,309	17.2	-70	-70	0	+10	86.5	0.1563
29	1,338	17.1	-70	-70	0	+10	83.7	0.10095
30	1,296	15.8	-70	-70	+10	+10	96.6	0.00678
31	1,302	14.5	-70	-70	+2	+2	98.5	0.0100
32	1,298	14.6	-70	-70	+2	+2	98.8	0.00992
33	1,122	19.9	-70	-70	+2	+2	98.6	0.0129
34	1,253	15.1	-70	-70	+10	+10	98.8	0.0157
35	1,227	14.7	-70	-70	0	0	97.3	0.0312
36	1,233	14.9	-68	-68	0	0	95.6	0.03595
37	1,263	14.9	0	0	+10	+10	82.0	0.1226
38	1,265	14.6	0	0	0	0	79.7	0.1567
39	1,228	14.9	-70	-70	-2	-2	98.0	0.0234
40	1,223	14.6	-70	-70	-2	-2	97.4	0.01749
41	1,212	15.2	-70	-70	-2	-2	97.8	0.0093
42	1,260	8.9	-70	-70	+2	+2	99.5	0.00741
45	1,285	8.7	-65	-65	+2	+2	97.8	0.0299
46	1,026	12.7	-70	-70	+2	+2	98.2	0.0282
51	1,290	8.5	-70	-70	+2	+2	96.5	0.0430
52	891	14.2	-70	-70	+2	+2	98.4	0.00652
53	1,031	12.9	-69	-69	+2	+2	92.7	0.00965
56	985	9.2	-60	0	0	+2	93.1	0.02222
57	1,067	8.5	-70	0	0	+2	83.7	0.0345
58	1,089	8.3	-70	0	0	0	80.4	0.03397
59	1,011	8.9	-70	0	0	0	91.3	0.01468
60	1,018	8.6	-70	0	0	+10	85.5	0.00293
61	952	9.3	-70	0	0	0	91.5	0.00917
62	994	8.7	-70	0	0	+10	82.0	0.00856
67	997	15.9	0	0	0	0	68.5	0.1283

Tests 30 to 41 were run with both spray towers in operation and at a total liquid flow rate of around 15 gal/min and a liquid pressure of about 56 psig. These tests were run to determine the effect of particle and droplet charging on the particulate collection efficiency and also the effect of oppositely charged and some polarity charged particles and droplets. For the oppositely charged case, the particles were charged negatively in a corona at 70 kV and the droplets were charged at 2 kV. In the same polarity case, both the particles and the droplets were charged negatively at 70 kV and 2 kV respectively. The test results show that oppositely charged particles and droplets give higher collection efficiencies. The results from the tests that were run to determine the effect of particle and droplet charging showed that particle charging and droplet charging both enhance collection efficiency of particles.

Tests 42 to 53 were run to obtain some additional data on the effect of liquid-to-gas flow ratio on the particle collection efficiency. During these tests, the liquid flow rate was further reduced to 9 gal/min. With the decrease in the liquid-to-gas flow rate, the collection efficiency of the particles was lowered somewhat. The test results for tests 30 to 53 illustrate the system's capability for high efficiency fine particle collection.

Tests 56 to 62 were conducted isolating tower #2. The tests were run at the inlet and outlet of the number #2 spray tower in an effort to isolate and measure the effect of liquor charging alone on the particle collection efficiency. The number #1 corona was operating but corona #2 and spray tower #1 were off. These tests were run at a constant liquid flow rate of 8 gal/min, constant gas residence time (constant gas flow rate), and constant voltage (70 kV) on corona #1. Tests were run at three different spray voltages: 0, 2, and 10 kV. The overall collection efficiencies of spray tower #2 do not appear to correlate well with the applied voltages. The electrostatic mist eliminator was inadvertently left on during these tests and thus these tests reflect also the particle collection efficiency of this unit. Therefore, in our opinion, no conclusions can be made concerning the effect of liquor charging on the particle collection efficiencies.

Test 67 was run as a baseline case with no charges on the particles and droplets with the electrostatic mist eliminator turned off (in other words the system was operated as a conventional spray droplet scrubber). The particle overall collection efficiency was found to be 68.5%.

B. PARTICLE COLLECTION EFFICIENCY AS A FUNCTION OF PARTICLE SIZE

The particle collection efficiency as a function of particle size is presented in Fig. VI-1 through Fig. VI-6. Fig. VI-1 shows the effect of the corona and spray voltages on the particle collection efficiencies. During these tests flooding of corona #2 was experienced resulting in the fairly low collection efficiencies in the submicron particle size range. Also note that the liquor-to-gas flow rate was quite high during these tests (about 26 gal/1000 acf) compared to later tests.

The effect of the corona SCA and the liquor-to-gas flow rate ratio are illustrated in Fig. VI-2. During these tests the liquor to spray tower #1 was shut off to eliminate the flooding of corona #2. Thus Fig. VI-2 shows that at the highest SCA (about 0.094 sq. ft./cfm) and L/G (about 32 gal/1000 acf), the particle collection efficiencies are of the highest magnitude (about 99%).

Based on tests 22 to 29, it was concluded that very high particle collection efficiencies were obtained by the system but at the expense of high liquid-to-gas flow rates. After changing the nozzles in both the spray towers and installing a screen mist eliminator downstream of spray tower #1, tests were run to determine the effect of charging voltages on the particle collection efficiencies. These test results are illustrated in Fig. VI-3. The liquor-to-gas flow rate during these tests was reduced to about 15 gal/1000 acf. The particle collection efficiencies in the whole particle size range increased significantly when charges were added to the particles and droplets. The highest particle collection efficiencies with these tests at constant SCA and constant L/G occurred at the particle charging voltage of 70 kV together with liquor charging voltage of 2kV.

The effect of the electrostatic charging polarities is shown in Fig. VI-4. The particle collection efficiencies were higher in the whole particle size range considered. The arrangement with opposite polarities provides the lower overall particle penetration (about 1.3%) compared to same polarities at about 2.1%.

The effect of the liquor-to-gas flow rate ratio on particle collection efficiency is shown in Fig. VI-5. The particle collection efficiencies in all the particle size ranges considered increased significantly upon increasing the L/G from about 8.6 gal/1000 acf to 14.6 gal/1000 acf. With this increase in L/G, the overall penetration decreased from about 2.9% to 1.4% (this was all at constant SCA and constant charging conditions).

Some tests were run at the inlet and outlet of the #2 spray tower in an effort to measure the effect of the liquor charging on the particle collection efficiency of the spray tower alone. The results are shown in Fig. VI-6. The #1 corona was operating but corona #2 and spray tower #1 were off. The electrostatic mist eliminator was inadvertently left on during these tests and thus these tests reflect also the particle collection efficiency of this unit. The particle collection efficiencies for these

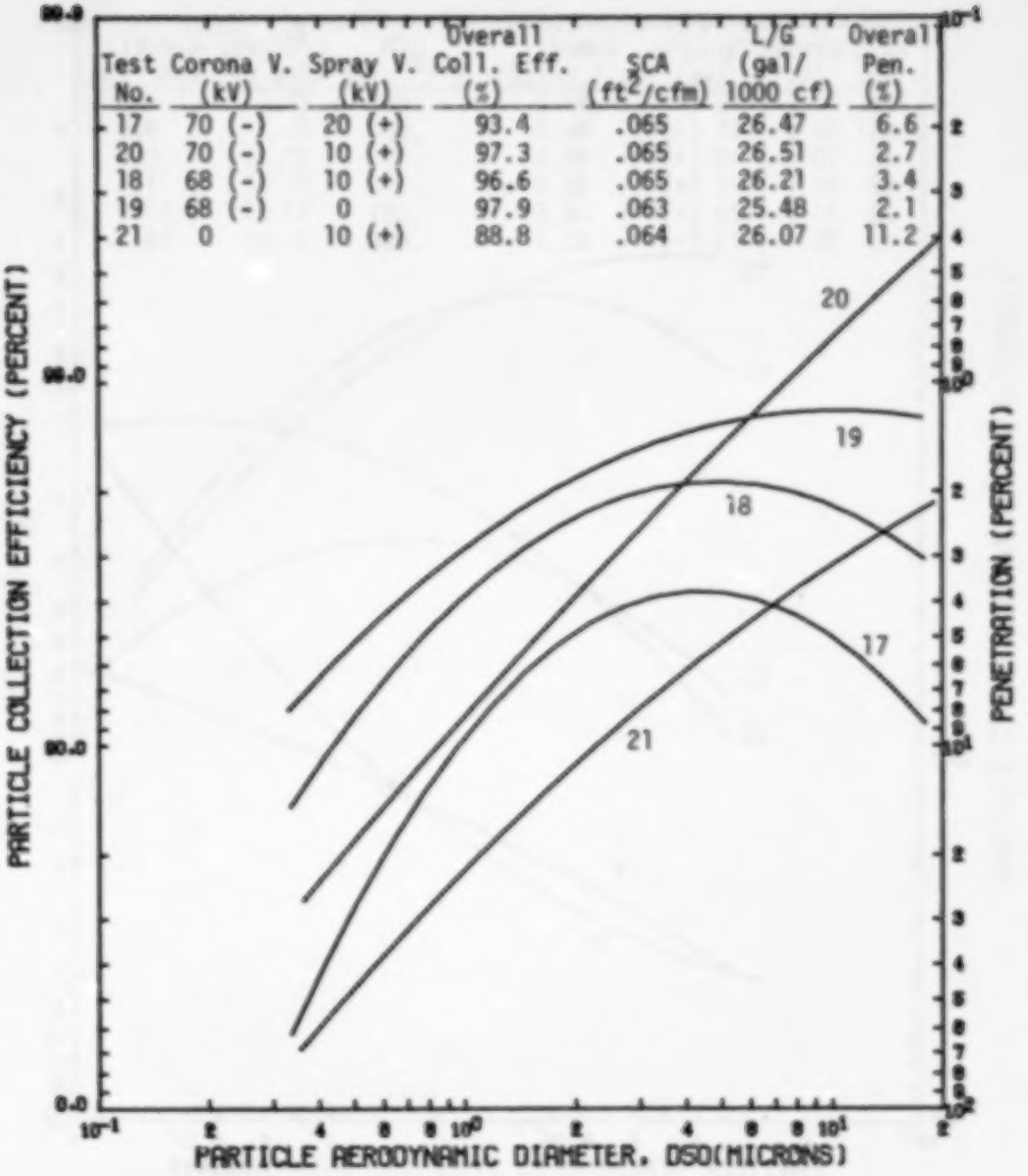
Test No. | Corona V. (kV) | Spray V. (kV) | Overall Coll. Eff. (%) | SCA (ft²/cfm) | L/G (gal/1000 cf) | Overall Pen. (%)
17 | 70 (-) | 20 (+) | 93.4 | .065 | 26.47 | 6.6
20 | 70 (-) | 10 (+) | 97.3 | .065 | 26.51 | 2.7
18 | 68 (-) | 10 (+) | 96.6 | .065 | 26.21 | 3.4
19 | 68 (-) | 0 | 97.9 | .063 | 25.48 | 2.1
21 | 0 | 10 (+) | 88.8 | .064 | 26.07 | 11.2
20
19
18
17
21
PARTICLE COLLECTION EFFICIENCY (PERCENT)
PENETRATION (PERCENT)
PARTICLE AERODYNAMIC DIAMETER, DSD(MICRONS)

Fig. VI-1 Effect of Corona and Spray Voltage on Particle Collection Efficiencies

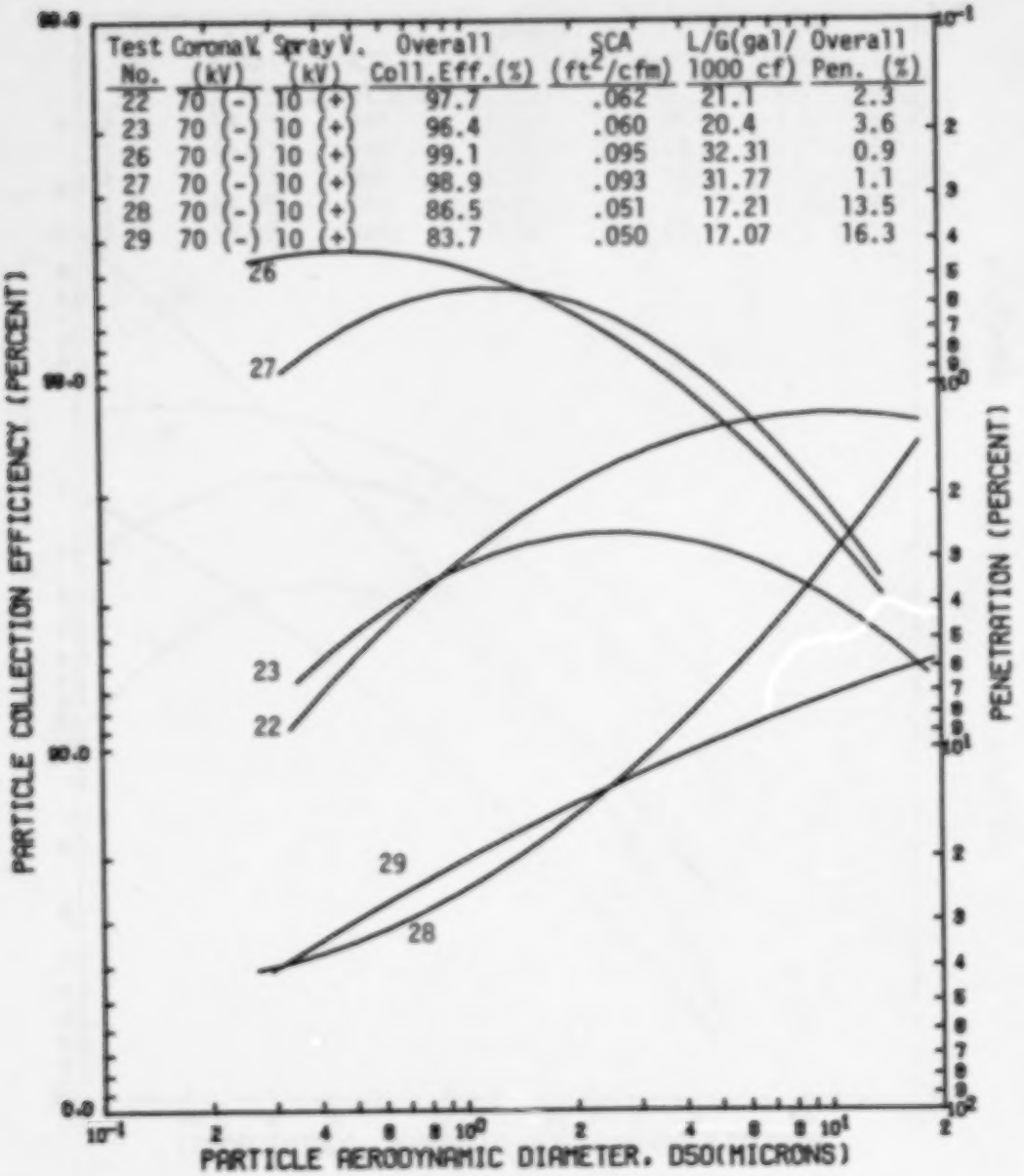
Test No. | Corona V. (kV) | Spray V. (kV) | Overall Coll. Eff. (%) | SCA (ft²/cfm) | L/G (gal/1000 cf) | Overall Pen. (%)
22 | 70 (-) | 10 (+) | 97.7 | .062 | 21.1 | 2.3
23 | 70 (-) | 10 (+) | 96.4 | .060 | 20.4 | 3.6
26 | 70 (-) | 10 (+) | 99.1 | .095 | 32.31 | 0.9
27 | 70 (-) | 10 (+) | 98.9 | .093 | 31.77 | 1.1
28 | 70 (-) | 10 (+) | 86.5 | .051 | 17.21 | 13.5
29 | 70 (-) | 10 (+) | 83.7 | .050 | 17.07 | 16.3
26
27
23
22
29
28
PARTICLE COLLECTION EFFICIENCY (PERCENT)
PENETRATION (PERCENT)
PARTICLE AERODYNAMIC DIAMETER, D50(MICRONS)

Fig. VI-2 Effect of SCA and L/G on Efficiency

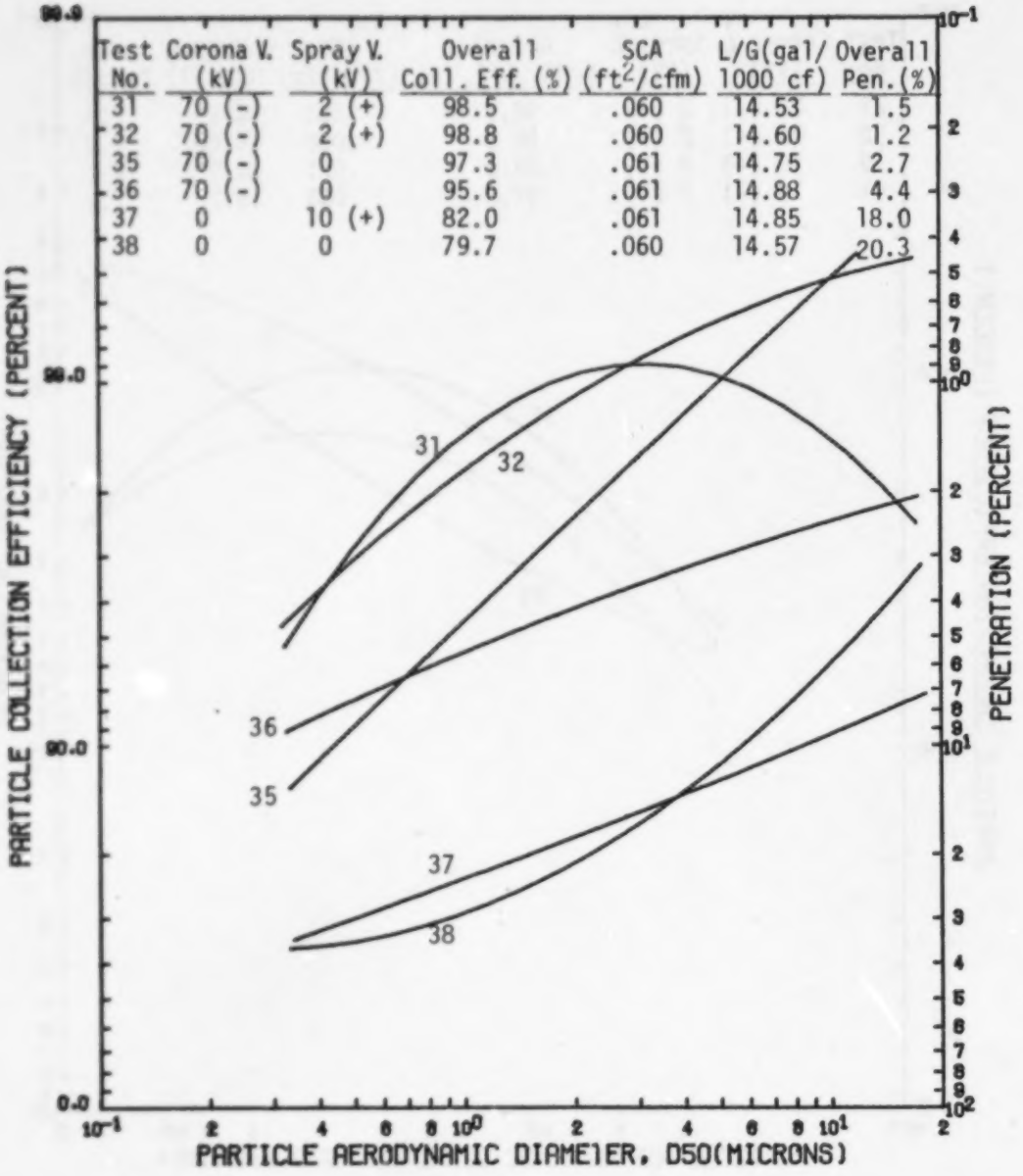
Test No. | Corona V. (kV) | Spray V. (kV) | Overall Coll. Eff. (%) | SCA (ft²/cfm) | L/G(gal/1000 cf) | Overall Pen.(%)
31 | 70 (-) | 2 (+) | 98.5 | .060 | 14.53 | 1.5
32 | 70 (-) | 2 (+) | 98.8 | .060 | 14.60 | 1.2
35 | 70 (-) | 0 | 97.3 | .061 | 14.75 | 2.7
36 | 70 (-) | 0 | 95.6 | .061 | 14.88 | 4.4
37 | 0 | 10 (+) | 82.0 | .061 | 14.85 | 18.0
38 | 0 | 0 | 79.7 | .060 | 14.57 | 20.3
PARTICLE COLLECTION EFFICIENCY (PERCENT)
PENETRATION (PERCENT)
PARTICLE AERODYNAMIC DIAMETER, D50(MICRONS)
31
32
36
35
37
38

Fig. VI-3 Effect of Charging Voltages on Particle Collection Efficiencies

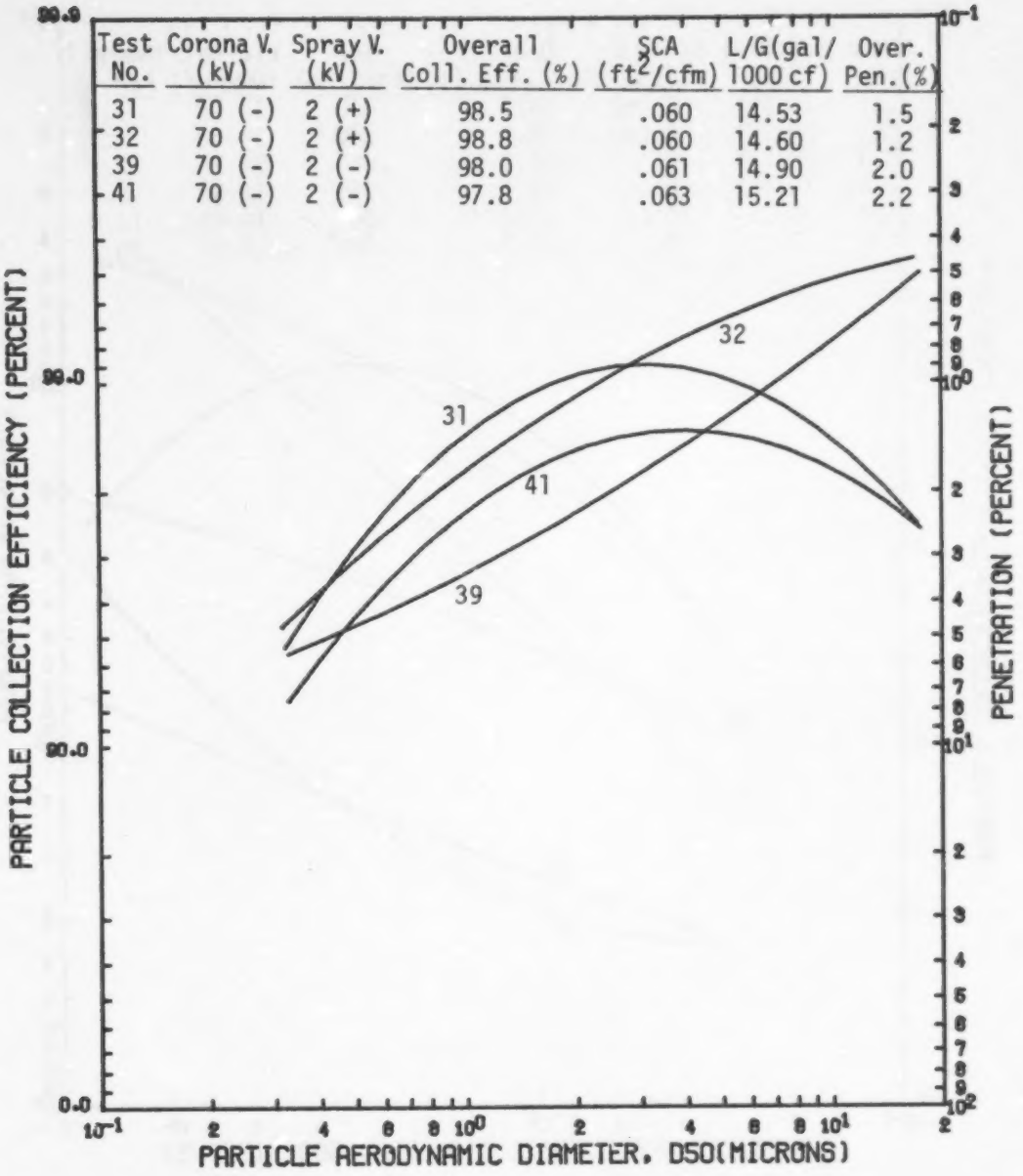
Test No. | Corona V. (kV) | Spray V. (kV) | Overall Coll. Eff. (%) | SCA (ft²/cfm) | L/G(gal/1000 cf) | Over. Pen.(%)
31 | 70 (-) | 2 (+) | 98.5 | .060 | 14.53 | 1.5
32 | 70 (-) | 2 (+) | 98.8 | .060 | 14.60 | 1.2
39 | 70 (-) | 2 (-) | 98.0 | .061 | 14.90 | 2.0
41 | 70 (-) | 2 (-) | 97.8 | .063 | 15.21 | 2.2
PARTICLE COLLECTION EFFICIENCY (PERCENT)
PENETRATION (PERCENT)
PARTICLE AERODYNAMIC DIAMETER, D50(MICRONS)
32
31
41
39

Fig. VI-4 Effect of Charging Polarities on Particle Collection Efficiencies

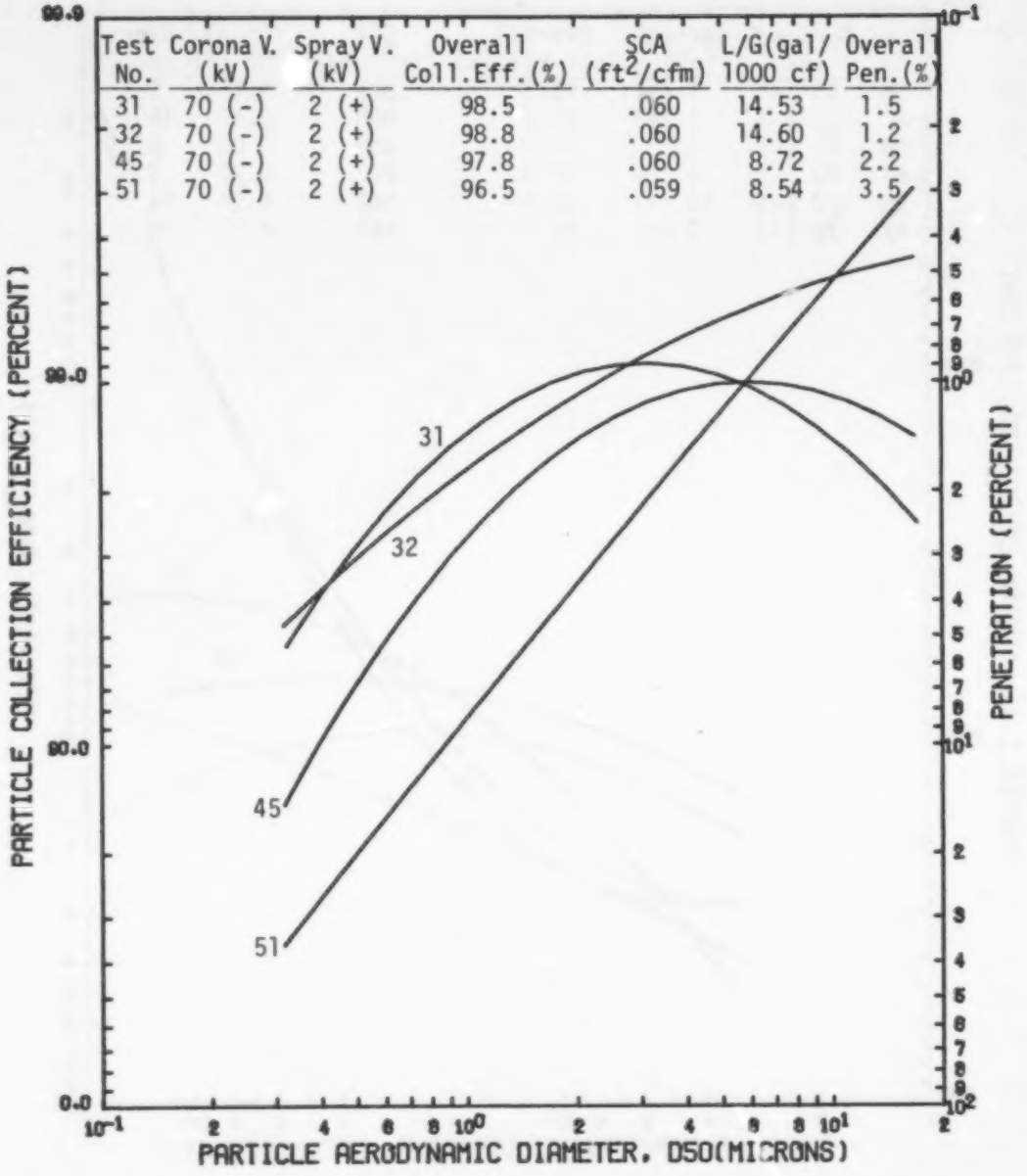
Test No. | Corona V. (kV) | Spray V. (kV) | Overall Coll.Eff.(%) | SCA (ft²/cfm) | L/G(gal/1000 cf) | Overall Pen.(%)
31 | 70 (-) | 2 (+) | 98.5 | .060 | 14.53 | 1.5
32 | 70 (-) | 2 (+) | 98.8 | .060 | 14.60 | 1.2
45 | 70 (-) | 2 (+) | 97.8 | .060 | 8.72 | 2.2
51 | 70 (-) | 2 (+) | 96.5 | .059 | 8.54 | 3.5
PARTICLE COLLECTION EFFICIENCY (PERCENT)
PENETRATION (PERCENT)
PARTICLE AERODYNAMIC DIAMETER, D50(MICRONS)
99.9
99.0
90.0
0.0
31
32
45
51

Fig. VI-5 Effect of Liquid-to-Gas Flow Rate Ratio on Particle Collection Efficiencies

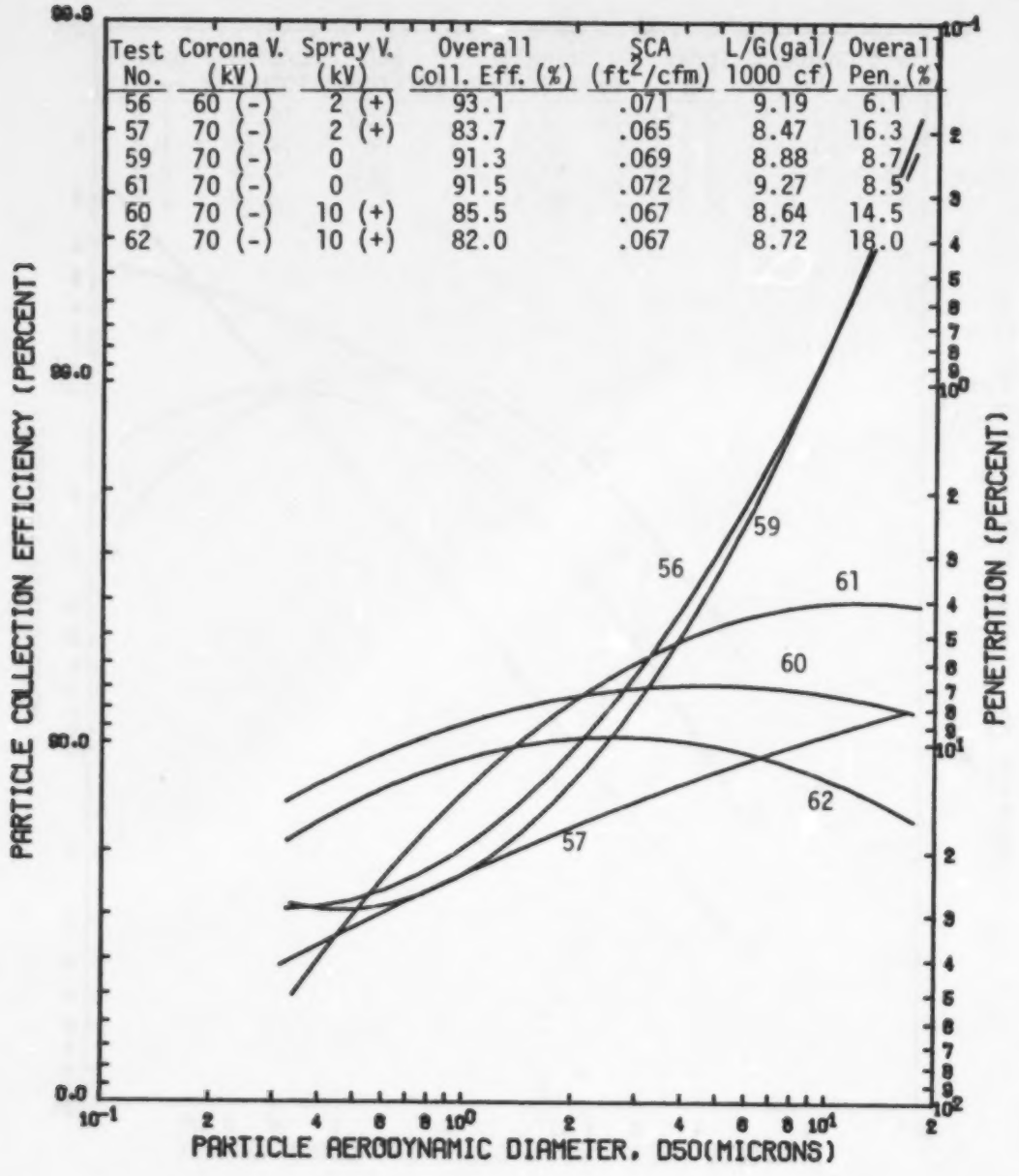
Test No. | Corona V. (kV) | Spray V. (kV) | Overall Coll. Eff. (%) | SCA (ft²/cfm) | L/G(gal/1000 cf) | Overal Pen.(%)
56 | 60 (-) | 2 (+) | 93.1 | .071 | 9.19 | 6.1
57 | 70 (-) | 2 (+) | 83.7 | .065 | 8.47 | 16.3
59 | 70 (-) | 0 | 91.3 | .069 | 8.88 | 8.7
61 | 70 (-) | 0 | 91.5 | .072 | 9.27 | 8.5
60 | 70 (-) | 10 (+) | 85.5 | .067 | 8.64 | 14.5
62 | 70 (-) | 10 (+) | 82.0 | .067 | 8.72 | 18.0
PARTICLE COLLECTION EFFICIENCY (PERCENT)
PENETRATION (PERCENT)
PARTICLE AERODYNAMIC DIAMETER, D50(MICRONS)
99.9
99.0
90.0
0.0
56
59
61
60
62
57

Fig. VI-6 Effect of Liquor Charging Voltages on Particle Collection Efficiency of Spray Tower Number 2

tests do not appear to correlate with the charging voltages. However, the highest collection efficiencies for the submicron particles occurred at the conditions of 70 kV on the corona and 10 kV on the liquor.

The particle collection efficiency as a function of particle size with no charging voltages and the electrostatic mist eliminator turned off is shown in Fig. VI-7. This test was conducted with both the spray towers on with a total liquor flow of 11 gpm (L/G of 15.9 gal/1000 acf).

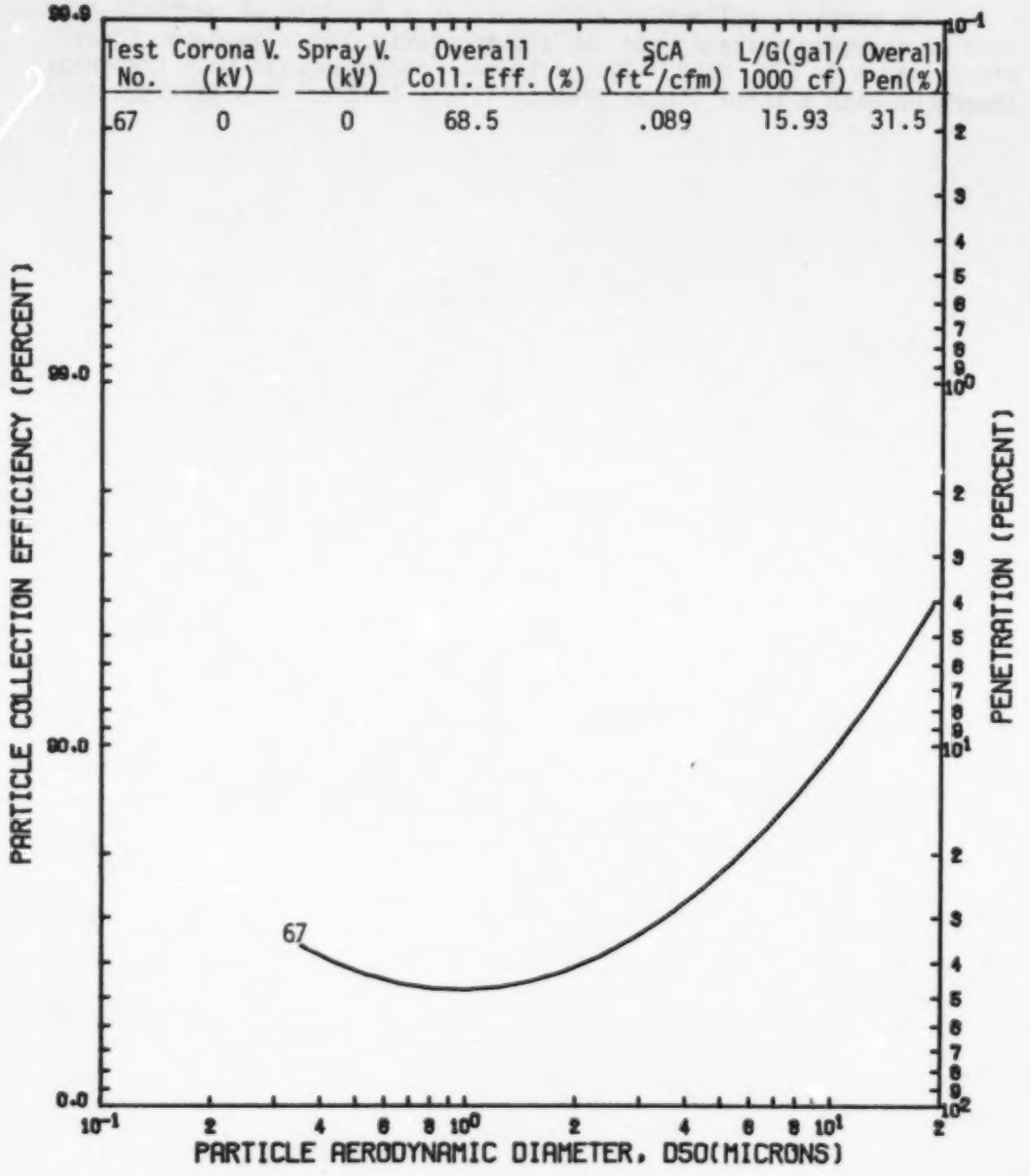

Fig. VI-7 Particle Collection Efficiency of Spray Towers 1 and 2 with Coronas and Mist Eliminator Off

C. PARTICLE SIZE DISTRIBUTION MEASUREMENTS

Fig. VI-8 illustrates the reproducibility of two simultaneous Mark 5 UW Cascade Impactor tests at the inlet to the Electrostatic Scrubber. The particle size distributions are almost identical below three micron diameter. The cascade impactors were located side by side about three to five feet downstream of a 180^{o} elbow and it is possible for some particle size stratification to occur here. The gas velocity in the duct was about 15 ft/sec during this test.

The inlet and outlet particle size distributions for the tests illustrated in the collection efficiency plots (Fig. VI-1 to Fig. VI-7) are presented in Fig. VI-9 to Fig. VI-21.

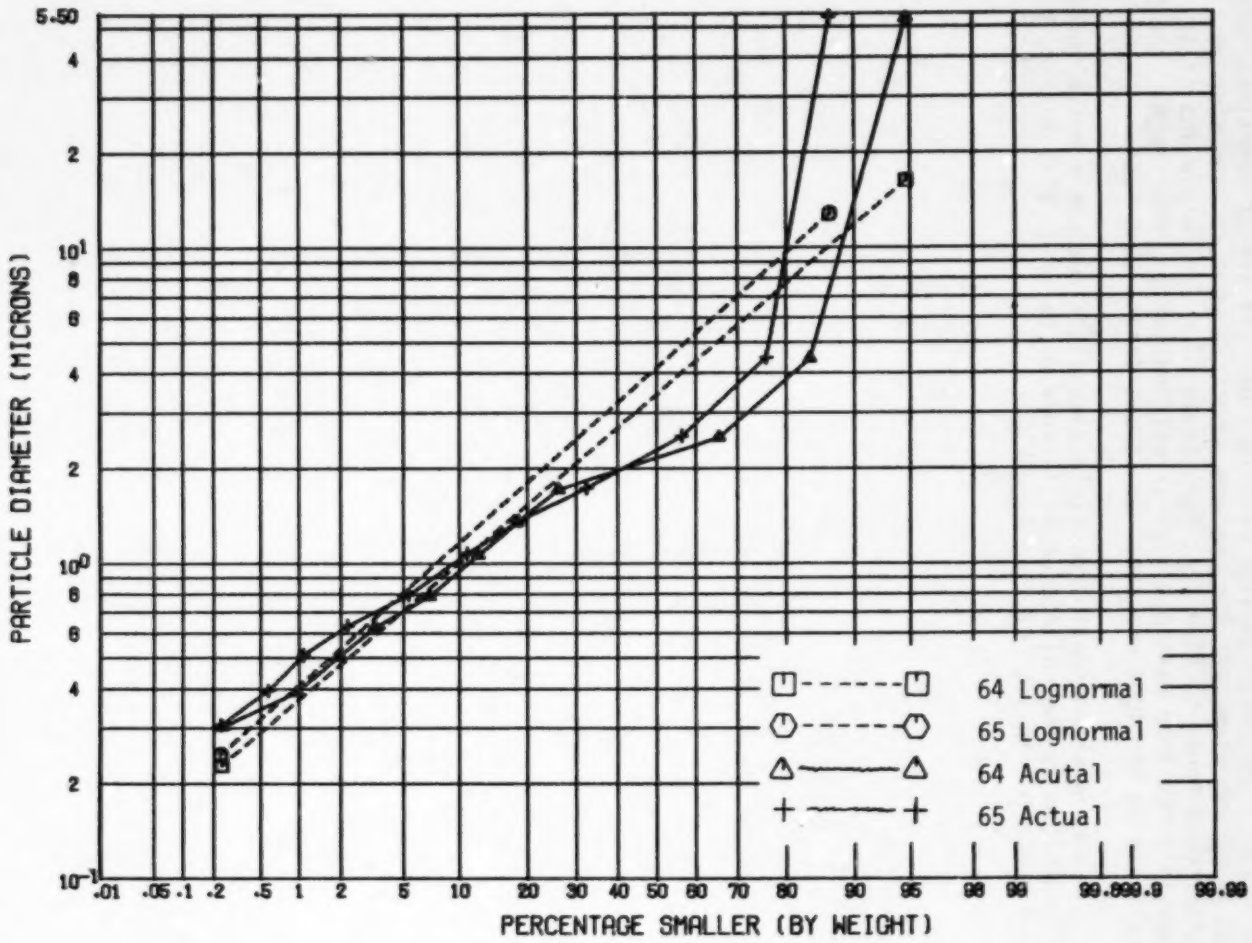

Fig. VI-8 Simultaneous Tests with Mark 5 UW Cascade Impactor at Inlet of Electrostatic Scrubber Pilot Plant

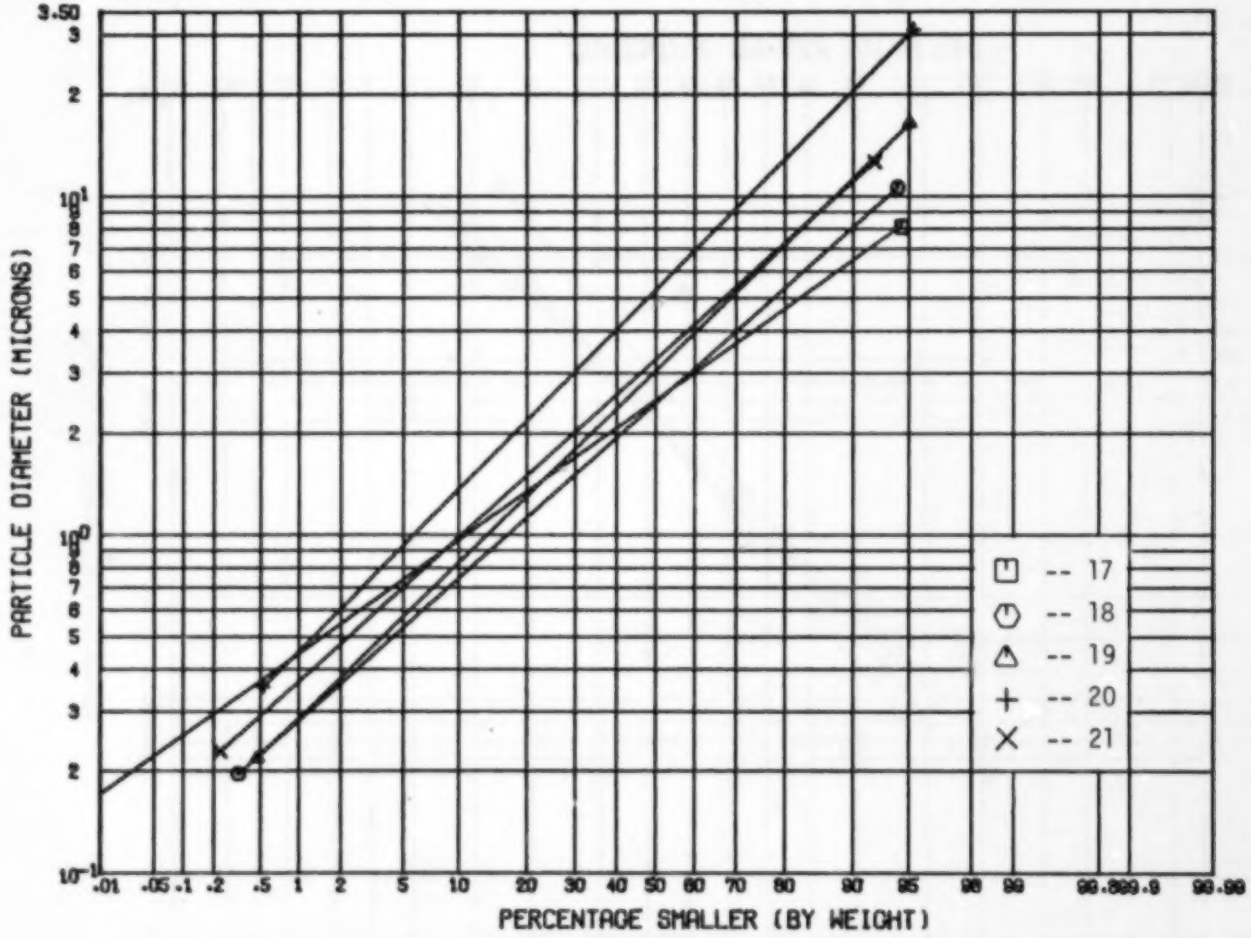

Fig. VI-9 Inlet Particle Size Distributions for Tests 17, 18, 19, 20, and 21

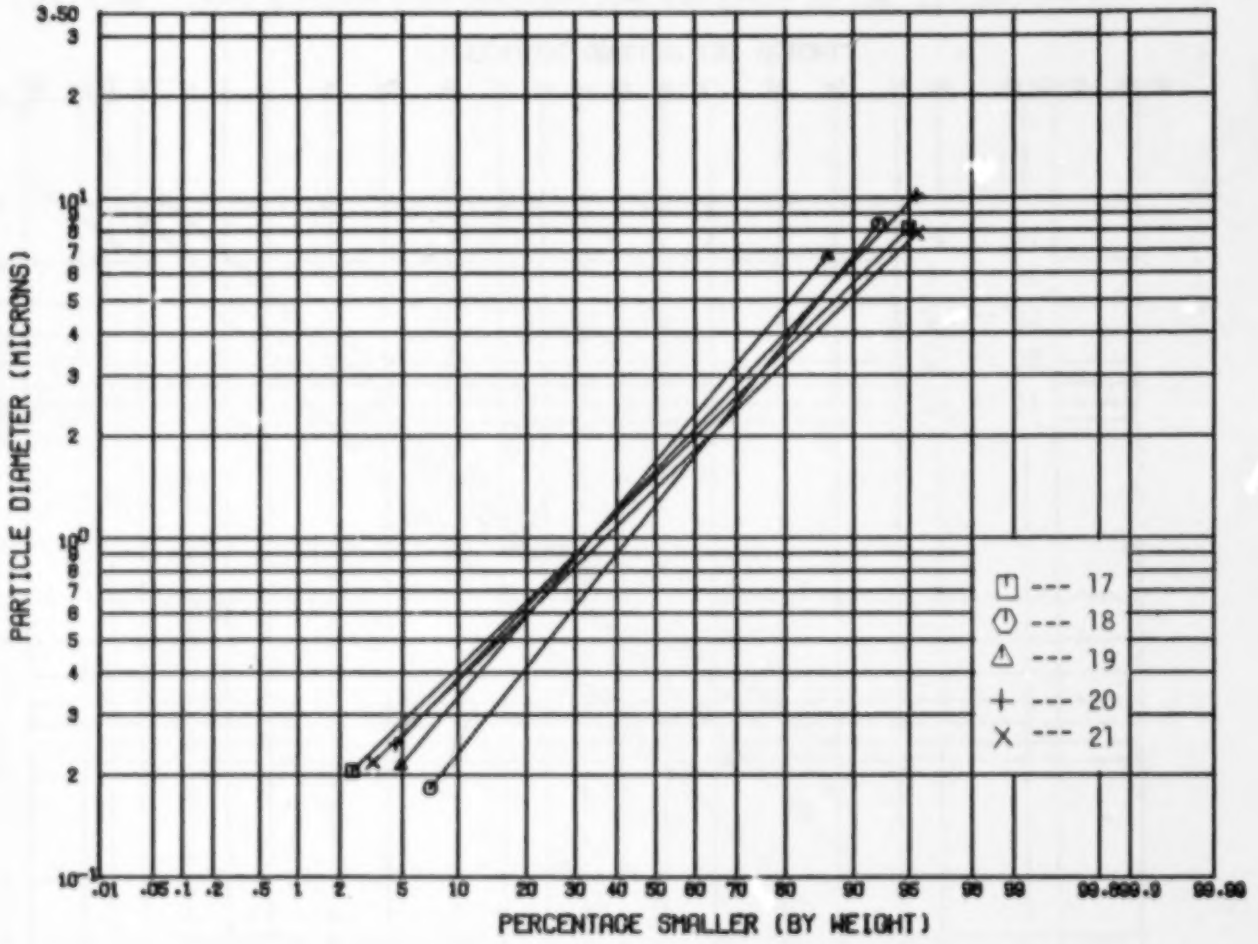

Fig. VI-10 Outlet Particle Size Distributions for Tests 11, 18, 19, 20, and 21

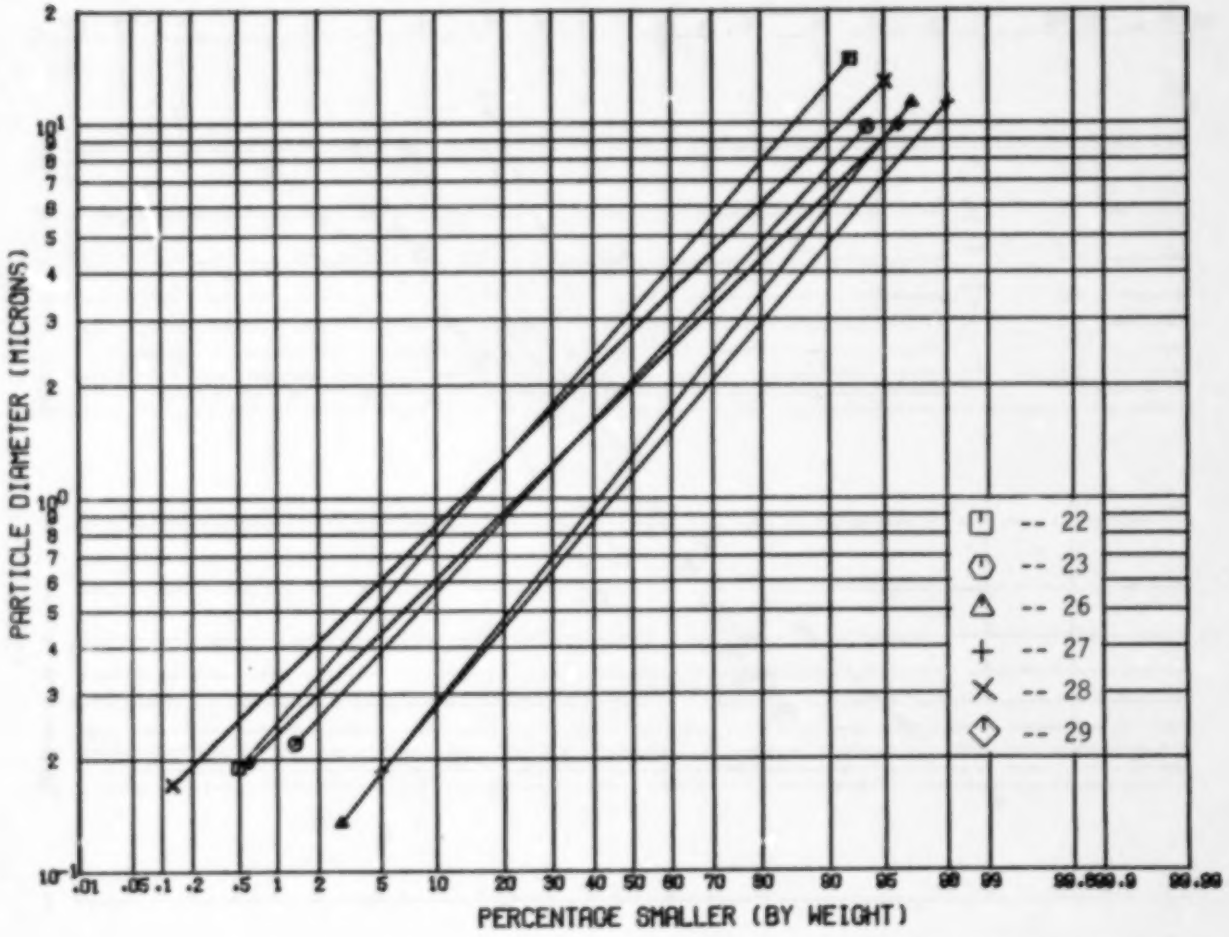

Fig. VI-11 Inlet Particle Size Distributions for Tests 22, 23, 26, 27, 28, and 29

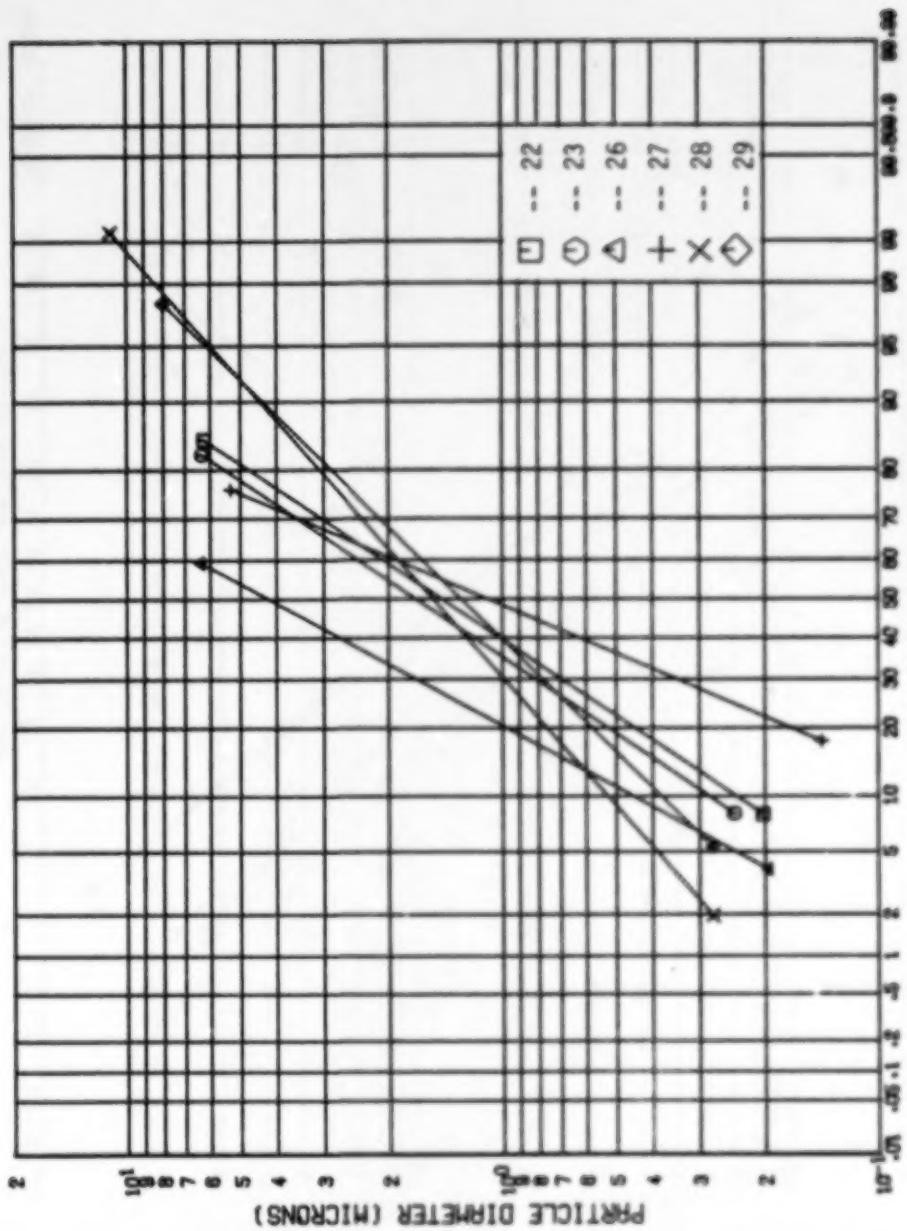

Fig. VI-12 Outlet Particle Size Distributions for Tests 22, 23, 26, 27, 28, and 29

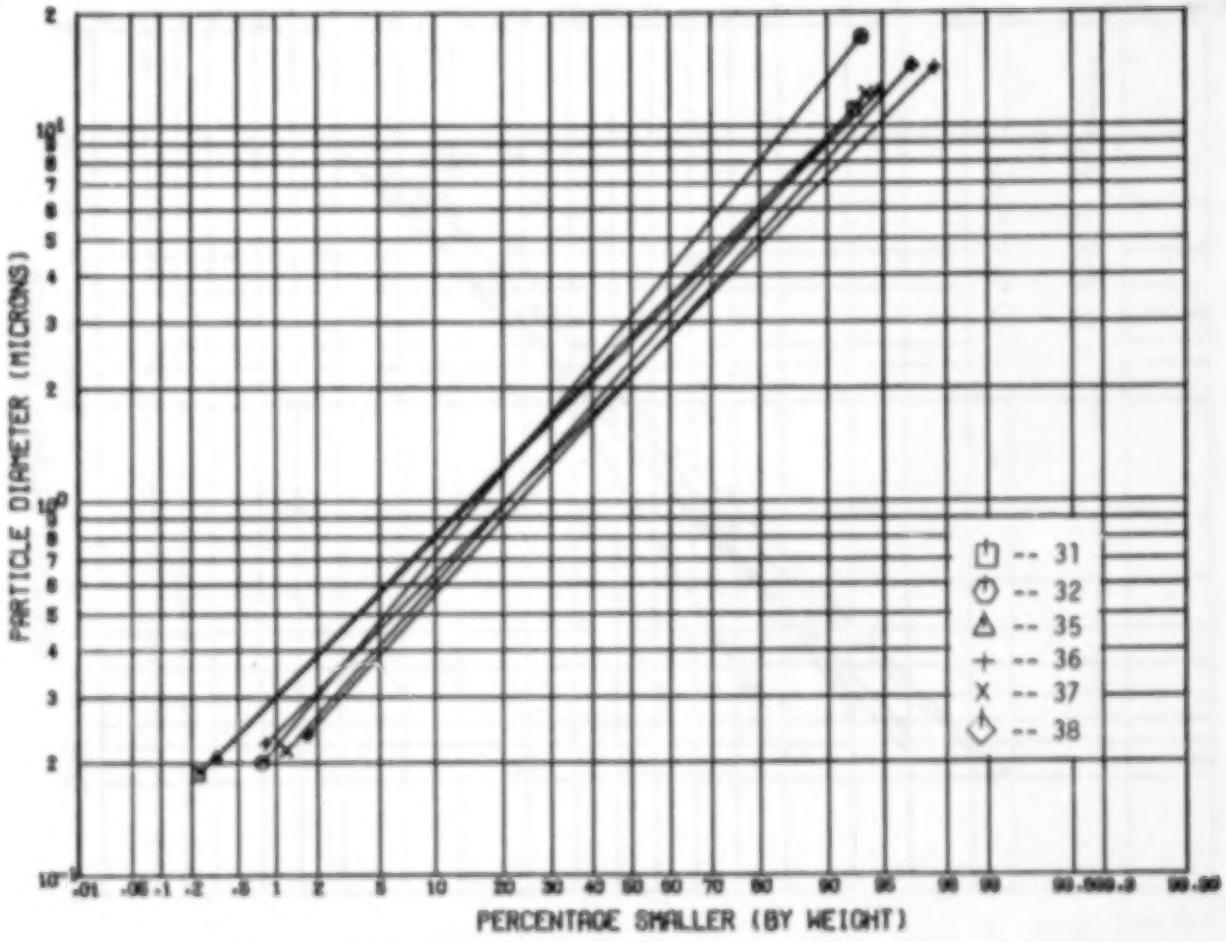

Fig. VI-13 Inlet Particle Size Distributions for Tests 31, 32, 35, 36, 37, and 38

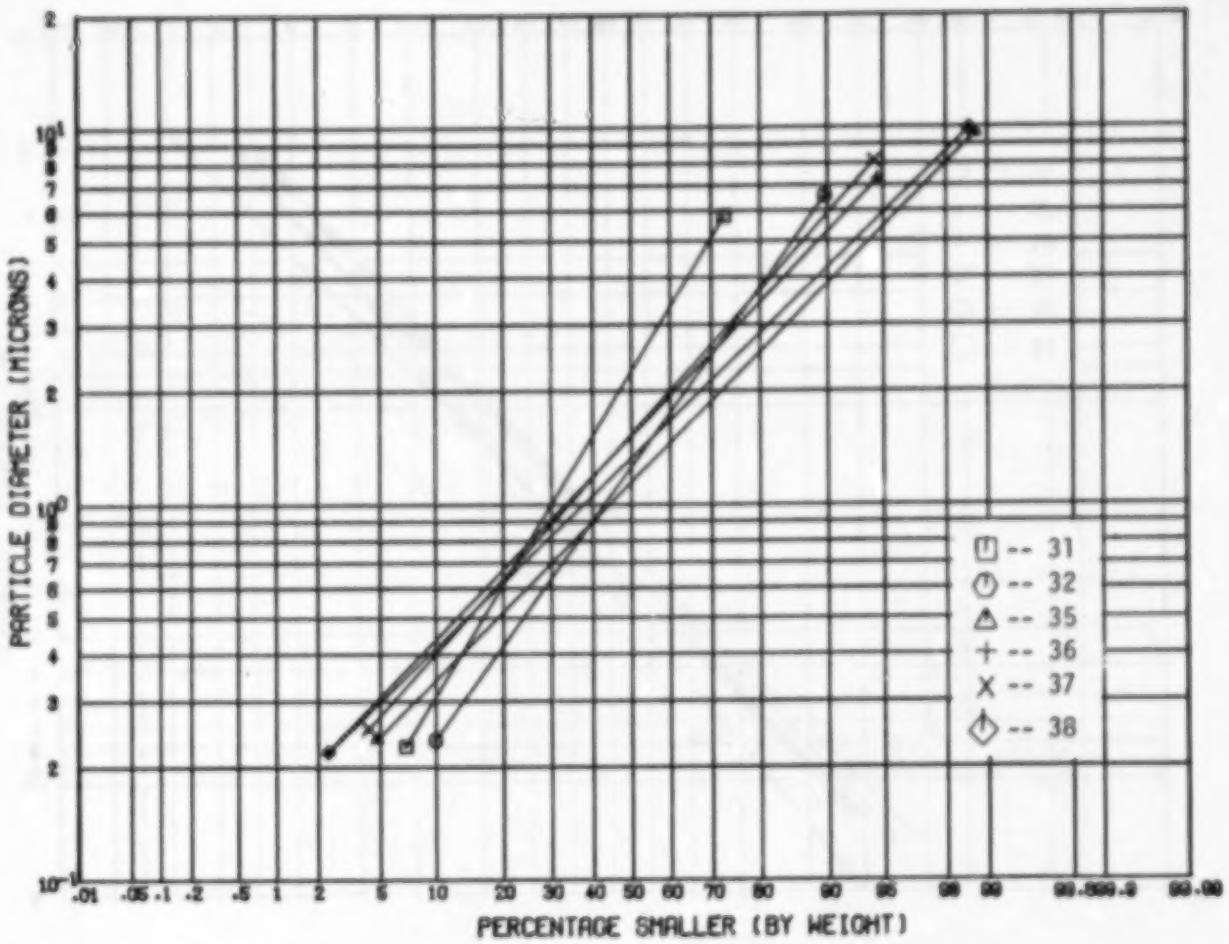

Fig. VI-14 Outlet Particle Size Distributions for Tests 31, 32, 35, 36, 34, and 38

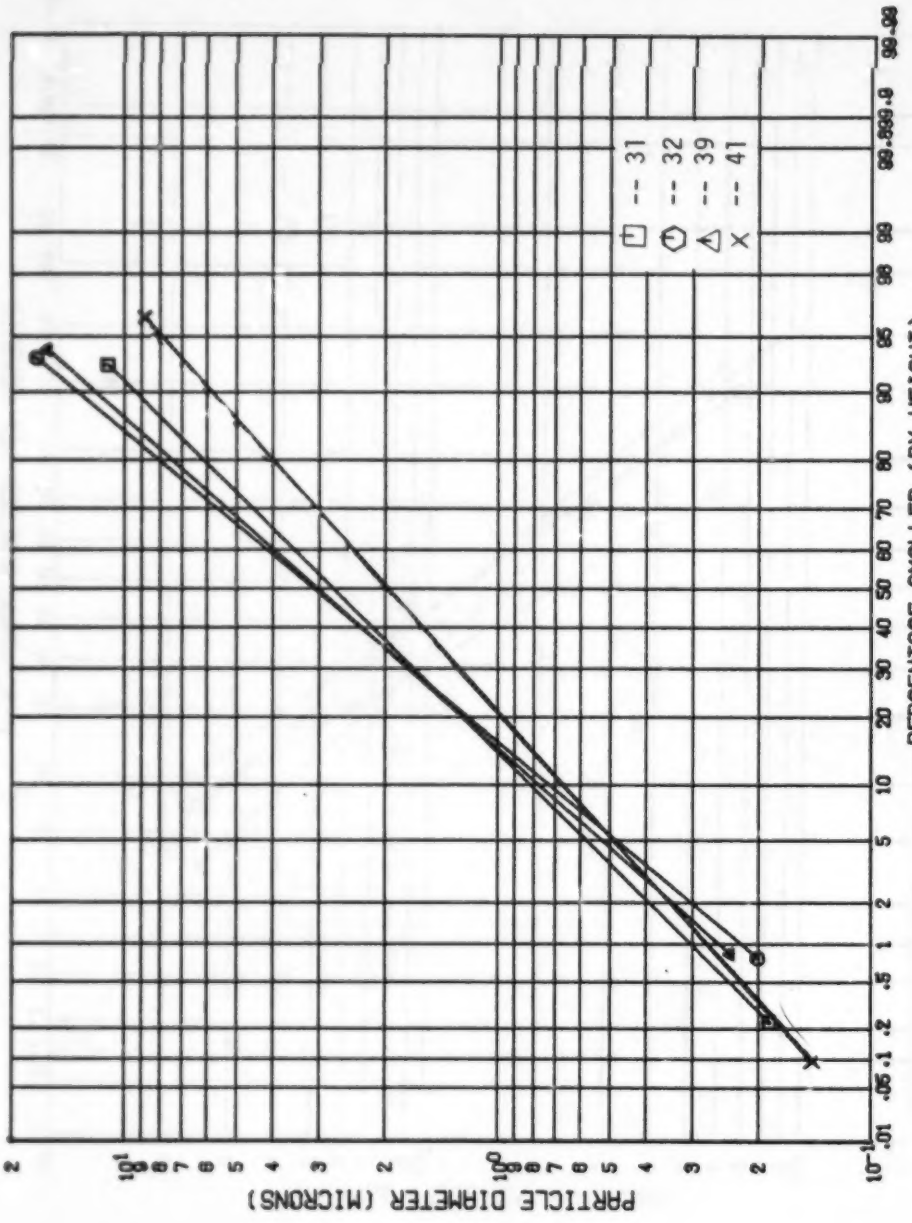

Fig. VI-15 Inlet Particle Size Distributions for Tests 31, 32, 39, and 41

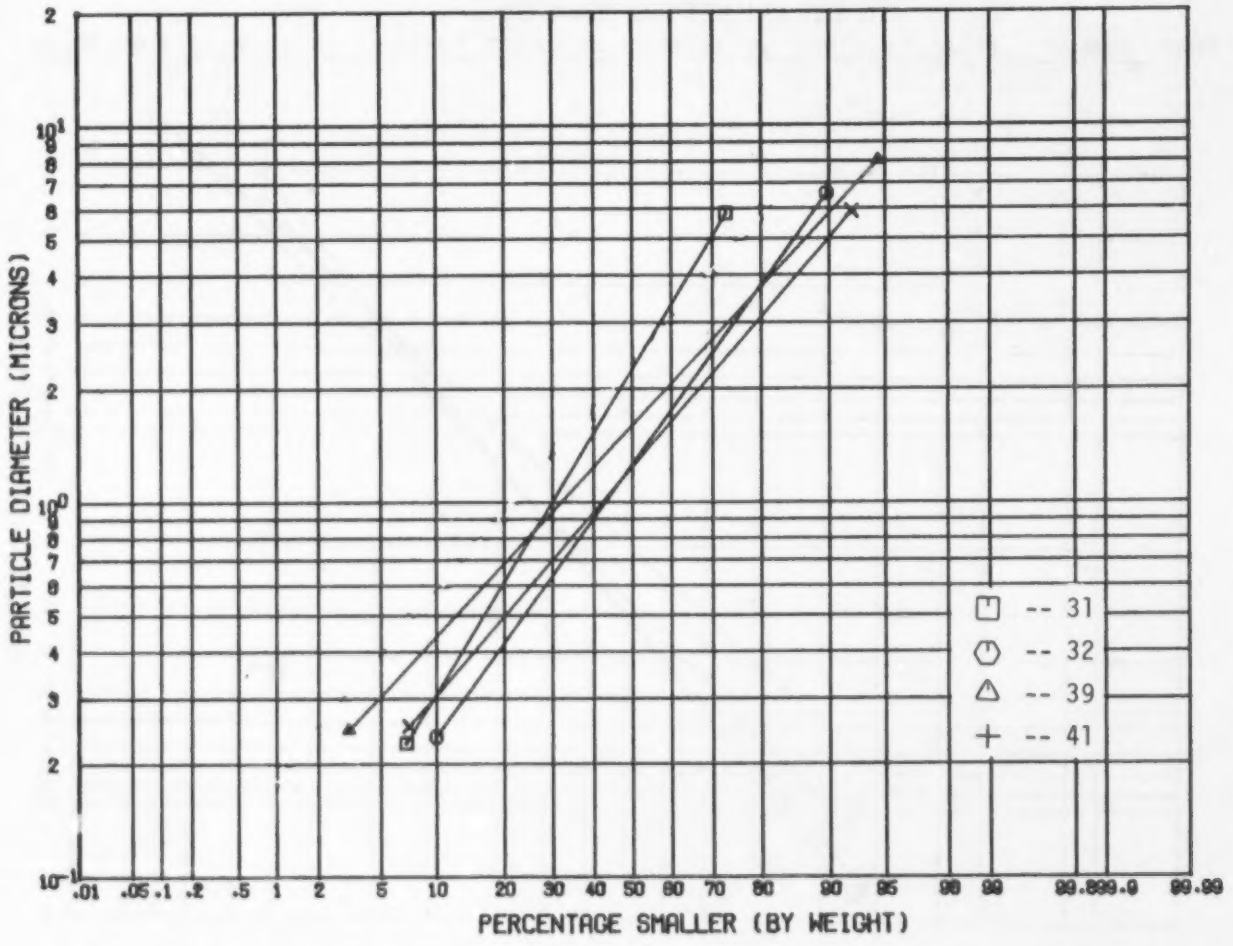

Fig. VI-16 Outlet Particle Size Distributions for Tests 31, 32, 39, and 41

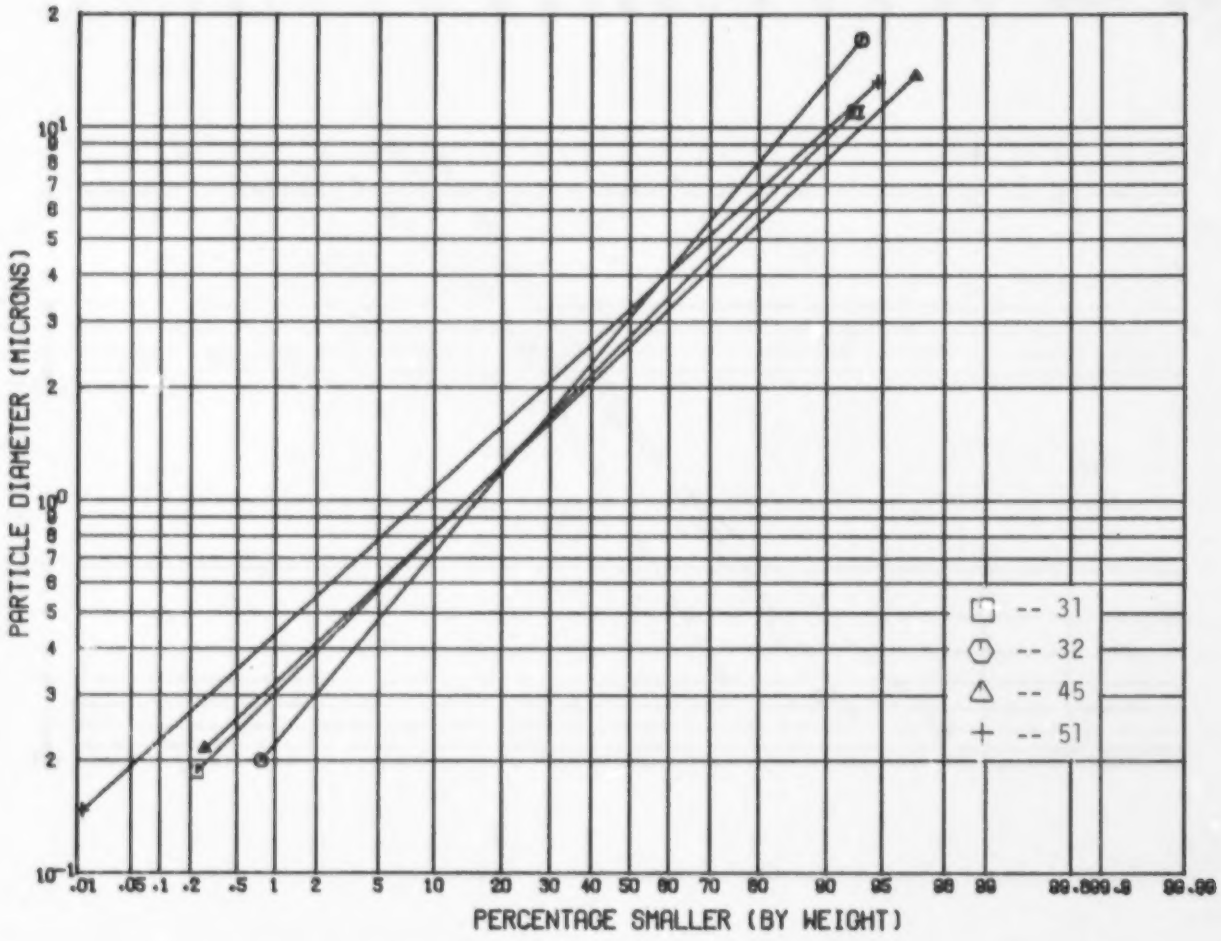

Fig. VI-17 Inlet Particle Size Distributions for Tests 31, 32, 45, and 51

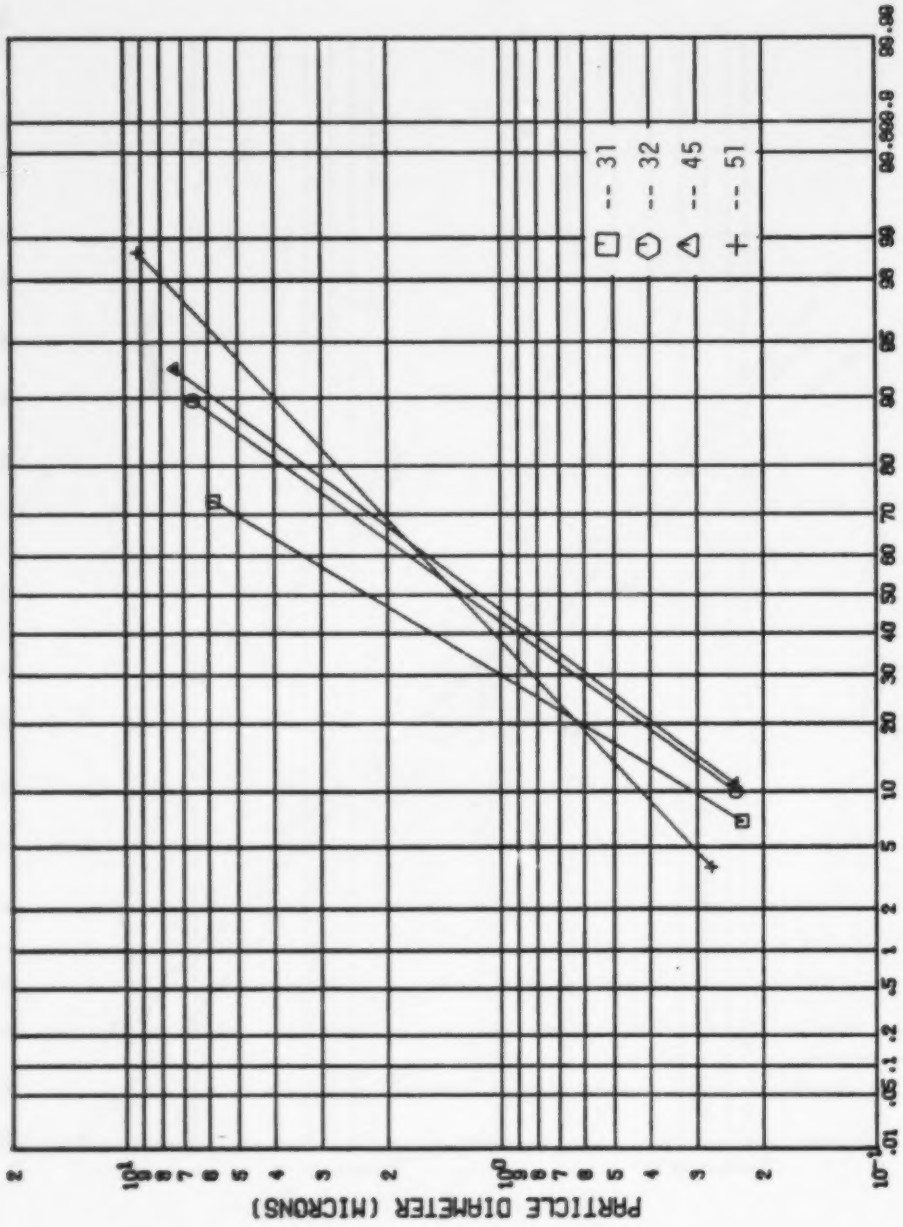

Fig. VI-18 Outlet Particle Size Distributions for Tests 31, 32, 45, and 51

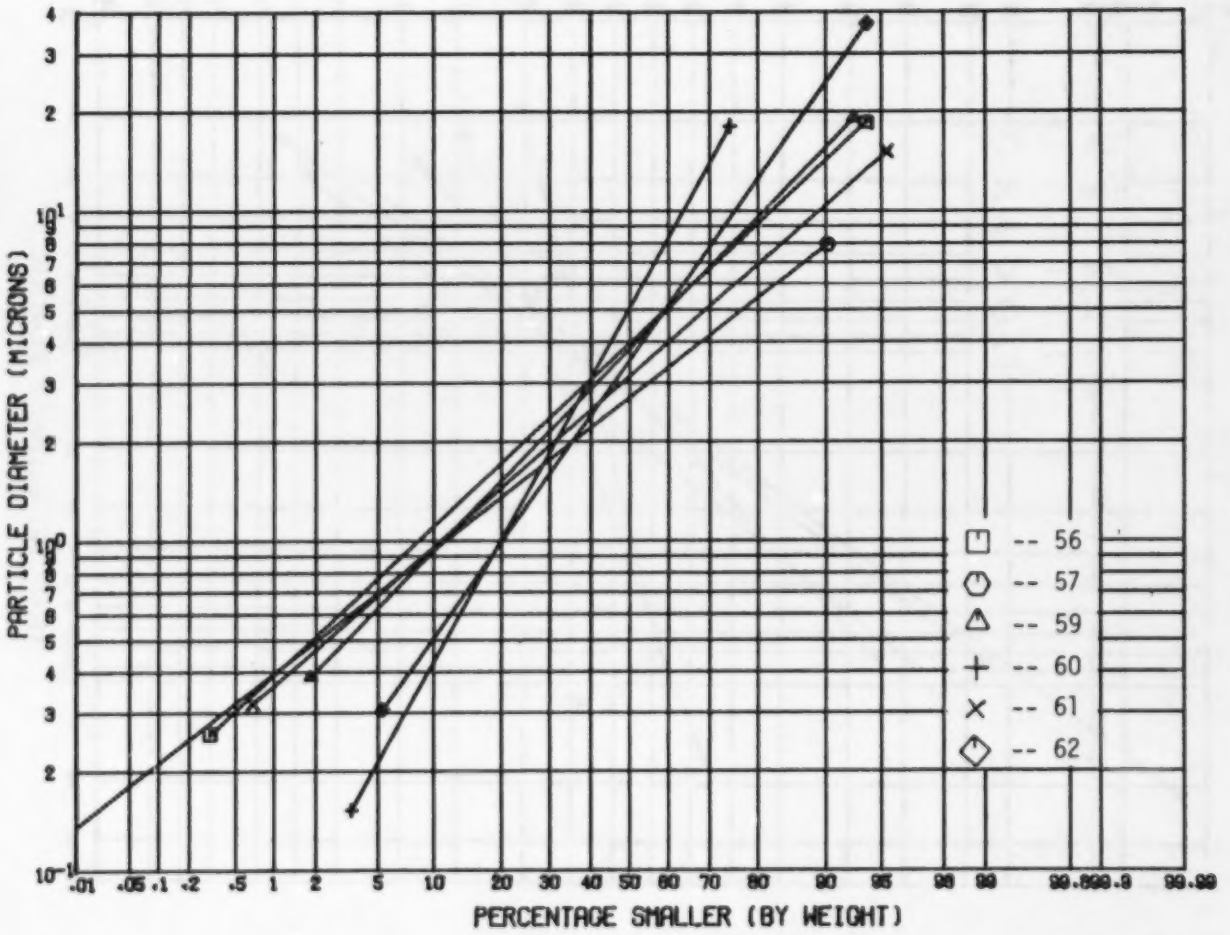

Fig. VI-19 Inlet Particle Size Distributions for Tests 56, 57, 59, 60, 61, and 62

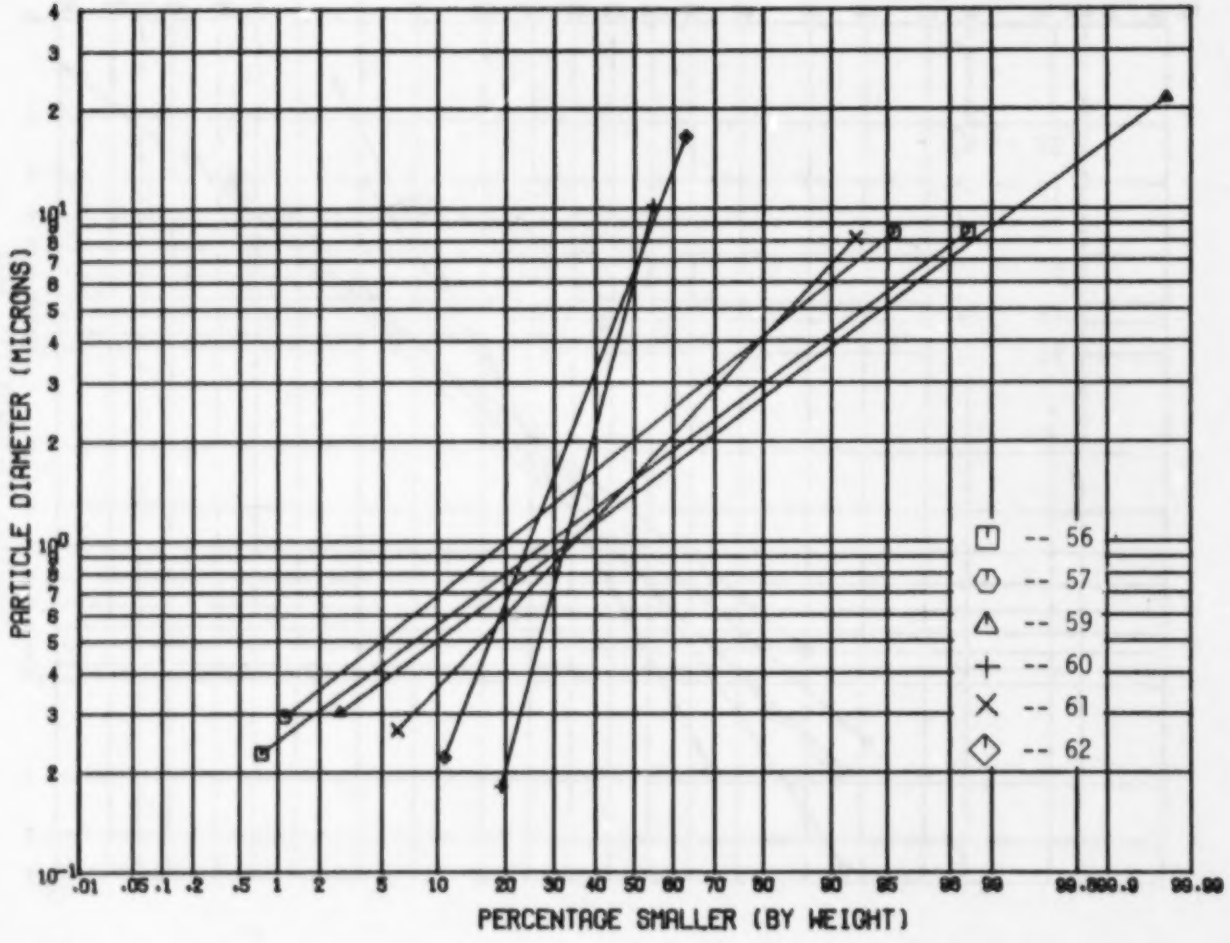

Fig. VI-20 Outlet Particle Size Distributions for Tests 56, 57, 59, 60, and 62

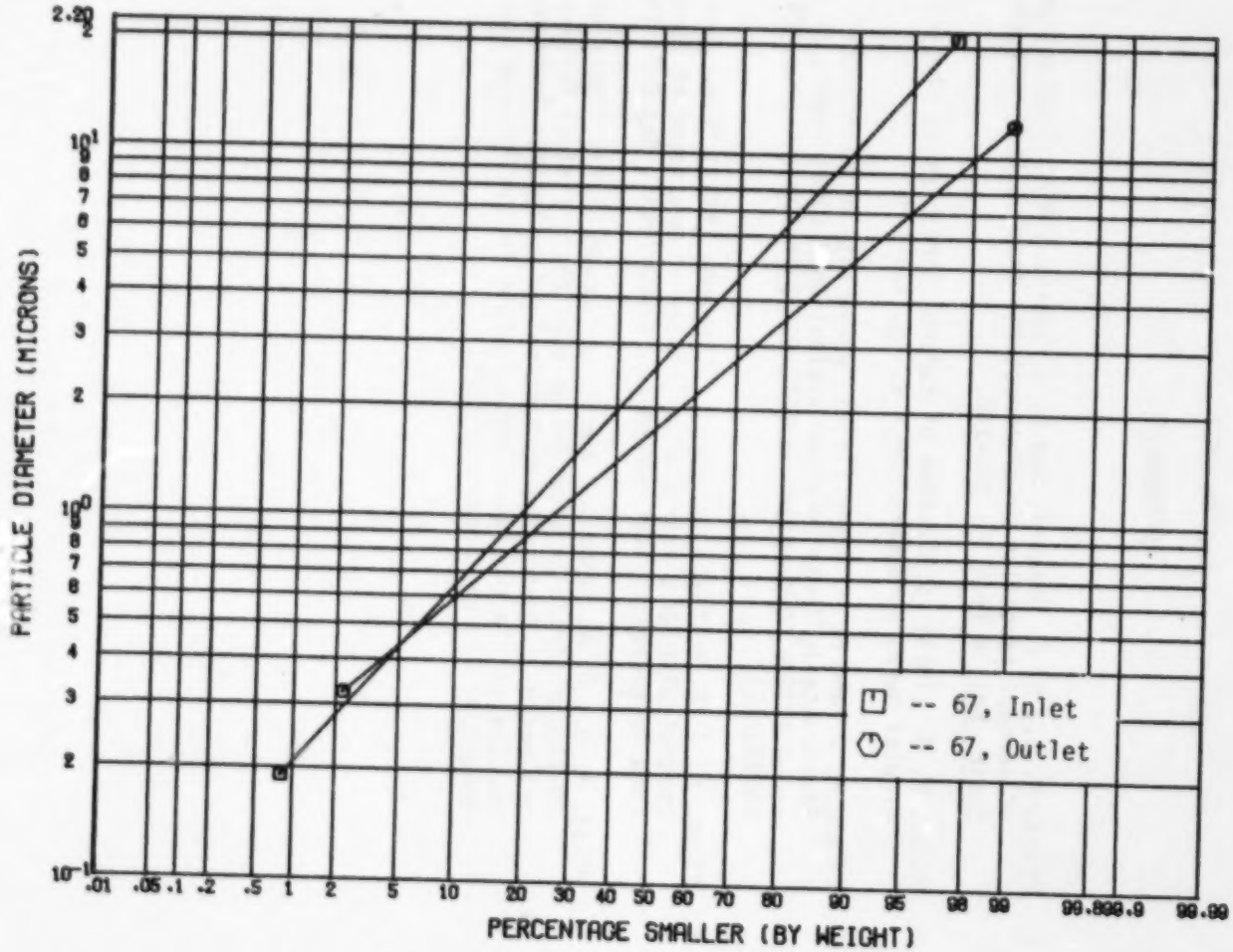

Fig. VI-21 Inlet and Outlet Particle Size Distributions for Test 67

Section VII

REFERENCES

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